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Updates to Models of Streamflow and Water Temperature for 2011, 2015, and 2016 in Rivers of the Willamette River Basin, Oregon

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Cover. A snorkeler recreating in the Willamette River upstream from McCartney Park during an extreme heat event, June 27, 2021. Photograph by Rose Wallick, U.S. Geological Survey.

Updates to Models of Streamflow and Water Temperature for 2011, 2015, and 2016 in Rivers of the Willamette River Basin, Oregon

By Laurel E. Stratton Garvin, Stewart A. Rounds, and Norman L. Buccola

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Conversion Factors

U.S. customary units to International System of Units

Multiply	By	To obtain
foot (ft)	0.3048	meter (m)
inch (in)	2.54	centimeter (cm)
mile (mi)	1.609	kilometer (km)
square mile (mi^2)	2.590	square kilometer (km^2)
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)
langley per hour (ly/hr)	11.6300	watts per square meter (W/m^2)

International System of Units to U.S. customary units

Multiply	By	To obtain
meter (m)	3.281	foot (ft)
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)

Temperature in degrees Celsius (°C) may be converted to degrees Fahrenheit (°F) as follows:

$$°F = (1.8 \times °C) + 32.$$

Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1927 (NAD 27) or the North American Datum of 1983 (NAD 83) as noted.

Elevation, as used in this report, refers to distance above the vertical datum.

Abbreviations

AWQMS	Ambient Water Quality Monitoring System
BR	branch
ECHO	Environmental Compliance History Online
ESA	Endangered Species Act
EWEB	Eugene Water and Electric Board
JDAY	Day of year (after Julian day)
LASAR	Oregon Department of Environmental Quality Laboratory Analytical Storage and Retrieval database
LCD	Local Climatological Data
MAE	mean absolute error
ME	mean error
NCEI	National Centers for Environmental Information
NOAA	National Oceanic and Atmospheric Administration
ODEQ	Oregon Department of Environmental Quality
PRIMET	primary meteorological (in reference to H.J. Andrews PRIMET station)
PS	point source
RAWS	Remote Automated Weather Station
RM	river mile
RMSE	root mean squared error
SRML	Solar Radiation Monitoring Laboratory
TR	tributary
TT	travel time
USACE	U.S. Army Corps of Engineers
USEPA	U.S. Environmental Protection Agency
USGS	U.S. Geological Survey
WB	waterbody
WBAN	Weather-Bureau-Army-Navy
WD	withdrawal
WWTP	wastewater treatment plant

Updates to Models of Streamflow and Water Temperature for 2011, 2015, and 2016 in Rivers of the Willamette River Basin, Oregon

By Laurel E. Stratton Garvin[1], Stewart A. Rounds[1], and Norman L. Buccola[2]

Abstract

Mechanistic river models capable of simulating hydrodynamics and stream temperature are valuable tools for investigating thermal conditions and their relation to streamflow in river basins where upstream water storage and management decisions have an important influence on river reaches with threatened fish populations. In the Willamette River Basin in northwestern Oregon, a two-dimensional, hydrodynamic water-quality model (CE-QUAL-W2) has been used to investigate the downstream effects of dam operations and other anthropogenic influences on stream temperature. By simulating the managed releases of water and various temperatures from the large Willamette Valley Project dams upstream of the modeling domain, these models can be used to investigate riverine temperature conditions and their relation to streamflow to determine where and when conditions are most challenging for threatened fish populations and how dam operations and flow management can affect and optimize thermal conditions in the river.

The original models were initially developed to simulate conditions in spring–autumn of 2001 and 2002. This report documents (1) the upgrade of the river models to CE-QUAL-W2 version 4.2 and (2) the update of those models to simulate conditions that occurred from March through October of 2011, 2015, and 2016. These years were selected to represent a range of climatic and hydrologic conditions in the Willamette River Basin, including a “cool, wet” year (2011), a “hot, dry” year (2015), and a “normal” year (2016). Six submodels comprise the modeling system updated in this report; each submodel can be run independently or run with the others as a system. These models include the Coast Fork and Middle Fork Willamette River submodel, which includes the Coast Fork and Middle Fork Willamette Rivers, the Row River, and Fall Creek; the McKenzie River submodel, which includes the South Fork McKenzie River downstream of Cougar Dam and the McKenzie River from its confluence with the South Fork McKenzie River to its mouth; the South Santiam River submodel, which comprises the South Santiam River from Foster Dam to the Santiam River; the North Santiam and Santiam River submodel, which includes the Santiam River and the North Santiam River downstream of Big Cliff Dam; the Upper Willamette River submodel, which includes the Willamette River from Eugene to Salem; and the Middle Willamette River submodel, which includes the Willamette River from Salem to Willamette Falls near Oregon City.

The models included in this report were originally developed, calibrated, and documented by other researchers. As part of the model updates described here, some model parameters were adjusted to improve stability and decrease runtime. Boundary conditions including meteorological, hydrologic, and thermal parameters were developed and updated for model years 2011, 2015, and 2016. In many cases, the data sources used to drive the 2001 and 2002 models were no longer available, which required the use of new data sources, the determination of a proxy record, or the development of appropriate estimation techniques. Goodness-of-fit statistics for the updated models show a good model fit, with the models simulating subdaily water temperatures at most comparable locations with a mean absolute error of generally less than 1 °C and often nearing 0.5 °C, depending on the individual submodel, and a reasonably low bias. The subdaily mean error for the South Santiam River submodel produced the highest bias of any of the submodels. Goodness-of-fit statistics indicate that the results may be biased cool (ranging from -0.43 °C in 2016 to -0.80 °C in 2011 for subdaily results), but the only water temperature data available for comparison on the South Santiam River is itself estimated, and those estimates are known to be too high in summer. Depending on future modeling needs, that submodel may warrant further refinement, along with additional data collection to properly define and minimize any model bias.

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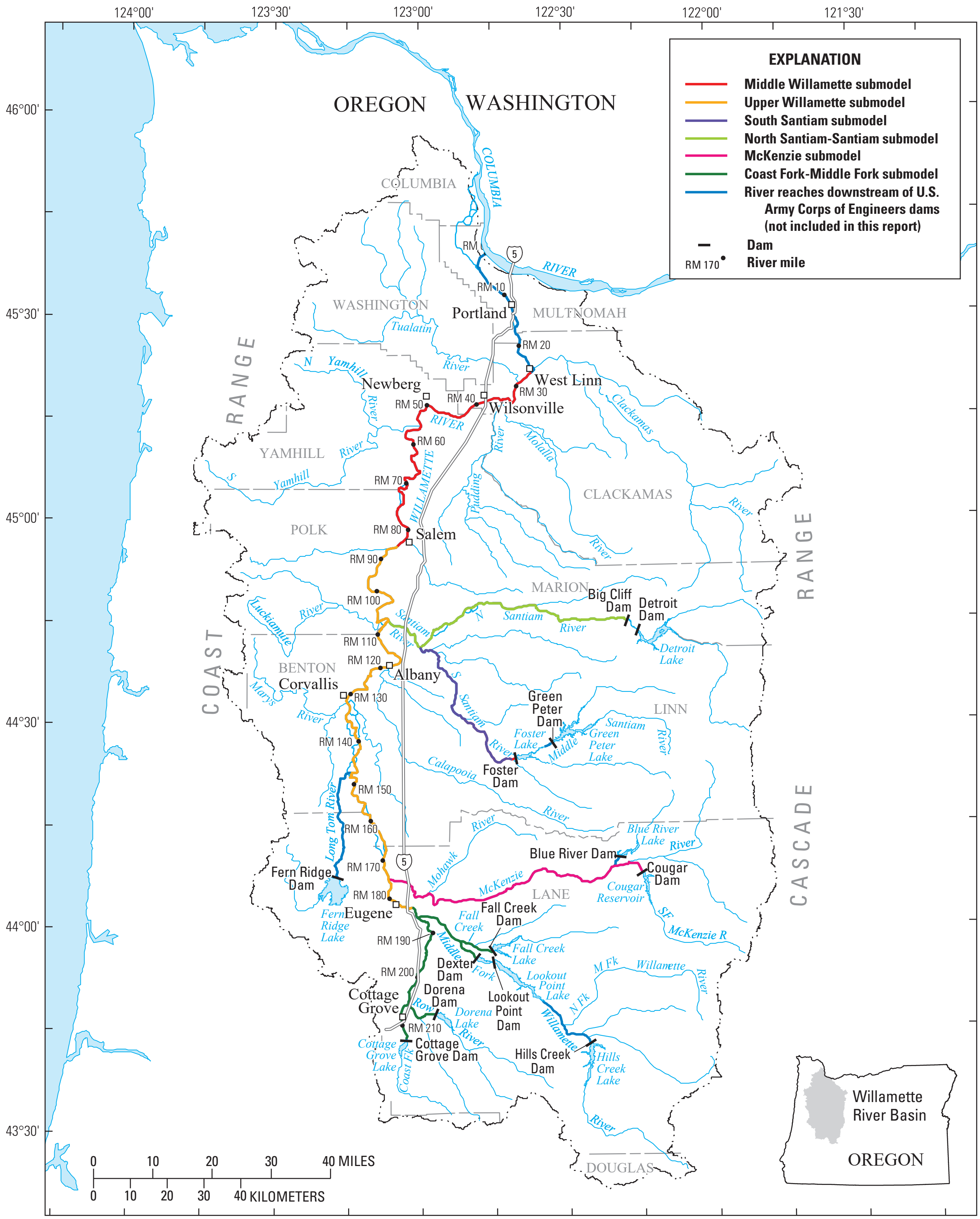
[2]U.S. Army Corps of Engineers, Portland District

Introduction

Populations of cold-water-adapted anadromous fish species, including spring-run Chinook salmon (*Oncorhynchus tshawytschya*) and winter-run steelhead (*O. mykiss),* were historically abundant in the Willamette River Basin of northwestern Oregon but those fish species are now listed as threatened under the Endangered Species Act (ESA) of 1973 (Public Law 93–205, 87 Stat. 884, as amended). An important factor in the decline of native anadromous fish populations in the basin is the presence and operation of 13 dams built and operated as the Willamette Valley Project by the U.S. Army Corps of Engineers (USACE) that restrict access to high-quality upstream habitat, contribute to the degradation and reduction of available downstream habitat, and alter the natural hydrologic and thermal regimes of the Willamette River and its dammed tributaries (National Marine Fisheries Service, 2008). Dam operations in recent years, and those still used in 2021, reduce the risk of downstream flooding and reduce the frequency and magnitude of peak flows while increasing summer low flows (Gregory and others, 2007; Risley and others, 2010a, 2010b, 2012; Wallick and others, 2013). Water releases from tall dams impounding stratified reservoirs often perturb seasonal temperature patterns in downstream reaches, delaying both spring warming and autumn cooling (Olden and Naiman, 2010; Rounds, 2010). Additionally, temperatures in the Willamette River commonly exceed regulatory criteria established by the Oregon Department of Environmental Quality (ODEQ) to protect native and threatened fish populations (Oregon Department of Environmental Quality, 2003, 2005, 2020b). Cumulatively, these conditions affect threatened fish species across multiple facets of their freshwater life stages, including juvenile habitat use, migration timing, growth, and survival; adult migration and spawning; development and survival of eggs; and egg hatch and fry redd emergence timing (Caissie, 2006; Keefer and others, 2010; Olden and Naiman, 2010).

In response to requirements imposed by a 2008 Biological Opinion addressing the ESA listing of winter steelhead and spring Chinook salmon (National Marine Fisheries Service, 2008), USACE has invested in a portfolio of research to better understand habitat and other requirements for healthy fish populations and in operational and infrastructure updates to provide fish passage and improve conditions for migrating and rearing fish populations downstream of USACE Willamette Valley Project dams. Previous research into these topics has documented the thermal effects of Willamette Valley Project dams on downstream reaches (Rounds, 2010; Risley and others, 2010b; Buccola and others, 2016), the effects of specific operational scenarios at key dams on downstream stream temperature (for example, Buccola and others, 2012, 2013, 2015; Buccola, 2017), and the conditions in off-channel environments in select reaches of the Willamette River (Smith and others, 2020), among others. More recently, USACE has supported multiple, cross-disciplinary efforts to better understand factors that limit the survival and reproductive success of threatened fish species and the potential for flow management or infrastructure changes at USACE dams to improve conditions for threatened fish populations. To support this effort, the U.S. Geological Survey (USGS) updated and developed models capable of simulating streamflow and temperature in the Willamette River and important tributaries downstream of USACE dams in the Willamette River Basin.

River models for all major tributaries and the Willamette River had been previously built using CE-QUAL-W2, a two-dimensional (laterally averaged) hydrodynamic and water-quality model jointly developed and maintained by USACE and Portland State University (Wells, 2019). This report documents updates to a set of CE-QUAL-W2 models of the Willamette River from Eugene to Willamette Falls, Fall Creek downstream of Fall Creek Dam, Row River downstream of Dorena Dam, Coast Fork Willamette River downstream of Cottage Grove Dam, Middle Fork Willamette River downstream of Dexter Dam, McKenzie River and South Fork McKenzie River downstream of Cougar Dam, South Santiam River downstream of Foster Dam, and North Santiam and Santiam Rivers downstream of Big Cliff Dam (fig. 1). Models were upgraded to CE-QUAL-W2 version 4.2, the most recently released version of the model (Wells, 2019), with additional USGS modifications to add specialized tracking capabilities utilized in other studies and configured for March through November of three recent years selected to represent a range of hydrologic and meteorological conditions in the Willamette River Basin. These years include 2011, a "cool, wet" year; 2015, a "hot, dry" year; and 2016, a "normal" year. Furthermore, these years include conditions that occurred after several structural and operational changes were made in the management of the Willamette Valley Project, such as (1) the construction of a selective withdrawal tower at Cougar Dam (completed in 2005), (2) the establishment of operational updates at Detroit Dam to better manage downstream water temperatures (after 2007), and (3) the continued implementation of modified flow-management strategies in use by USACE since approximately 2001. By applying this range of model years with a set of operational and management scenarios, results of simulations by the CE-QUAL-W2 models can provide insights into a range of thermal conditions and the sensitivity of stream temperature to flow-management strategies and dam operations in the Willamette River and its tributaries.



Base map modified from U.S. Geological Survey and other digital data sets (1:2,000,000; 1:100,000).
Projection: Oregon Lambert Conformal Conic, NAD1983, NAVD1988.

Figure 1. Locations of the river network, modeled river reaches, and major reservoirs in the Willamette River Basin, Oregon. Modified from Rounds (2007).

Description of Study Area

The Willamette River Basin in northwestern Oregon is the site of the Willamette Valley Project, a system of 13 dams and reservoirs, multiple riverbank protection projects, and hatchery programs operated by the USACE for the Willamette River and its tributaries. Authorized purposes include flood risk management, irrigation, navigation, hydropower, fish and wildlife, protection and improvement of water quality, recreation, and water supply (U.S. Army Corps of Engineers, 2019). The approximately 11,500 square mile (mi^2) basin includes parts of three distinct regions: the Coast Range to the west, the Willamette Valley, and the Cascade Range to the east. The Willamette Valley is the most highly productive and diverse agricultural region in the state, as well as the site of Oregon's largest metropolitan areas, including the cities of Portland, Salem, Eugene, and Albany (Conlon and others, 2005). Most Willamette Valley Project dams are located on Willamette River tributaries draining the Cascade Range (fig. 1), which contribute most of the flow inputs to the Willamette River.

The climate of the Willamette River Basin is defined by cool, wet winters and warm, dry summers; approximately 70 to 80 percent of annual precipitation typically falls between October and March and little precipitation occurs during summer (Wentz and others, 1998). Precipitation in the relatively low-elevation Coast Range and in the Willamette Valley falls mostly as rain, whereas the higher elevations of the Cascade Range receive up to 130 inches of snow annually (PRISM Climate Group, 2020). Streamflow reflects seasonal weather patterns, with peak flows coinciding with winter storms, relatively high flows during spring snowmelt, and lowest flows near the end of the summer dry season. Accordingly, dams impounding major reservoirs in the basin are drawn down in autumn and winter to provide space for flood risk management, and are allowed to fill in late spring. Annual reservoir storage is used, among other purposes, to provide water for municipal and agricultural use and to augment streamflow during summer (U.S. Army Corps of Engineers, 2019). Flow augmentation authorized for navigational purposes (and, secondarily, water-quality benefits) has been implemented in the Willamette River since the early 1950s (National Marine Fisheries Service, 2008), but augmentation to meet minimum streamflow benchmarks for ecosystem health was not formally recognized until the 2008 Biological Opinion was issued. Higher streamflows are believed to provide better habitat conditions and water quality for aquatic species, particularly in summer when stream temperatures are highest (National Marine Fisheries Service, 2008). More detailed sub-basin descriptions are provided with the discussion of the individual submodels, later in this report.

Purpose and Scope

This report documents model modifications, boundary condition data sources or estimation methods, and goodness-of-fit statistics for two-dimensional, stream-temperature models of six river reaches in the Willamette River Basin (fig. 1). The models documented in this report have been used, and may continue to be used, in multiple analyses to help the USACE and other groups and agencies better understand thermal conditions in the Willamette River and its tributaries as well as the sensitivity of stream temperature to flow-management strategies or other actions. The complete model domain is referred to in this report as the "river system model" and consists of the following six submodels:

- **Coast Fork and Middle Fork Willamette River submodel:** Includes Fall Creek downstream of Fall Creek Dam, the Row River downstream of Dorena Dam, the Coast Fork Willamette River downstream of Cottage Grove Dam, the Middle Fork Willamette River downstream of Dexter Dam, and approximately 2 miles of the Willamette River downstream of the Coast Fork/Middle Fork confluence. Output from the downstream boundary of this model, at river mile (RM) 185.3 (the Hwy 126 bridge in Springfield, Oregon), is used as input to the Upper Willamette River submodel.

- **McKenzie River submodel:** Includes the South Fork McKenzie River downstream of Cougar Dam and the McKenzie River from its confluence with the South Fork McKenzie River at RM 56.3 to its confluence with the Willamette River, as well as the Leaburg and Walterville Canals, which divert flow for power generation before returning that water to the McKenzie River farther downstream. Output from the downstream boundary of this model is used as a tributary inflow to the Upper Willamette River submodel.

- **South Santiam River submodel:** Comprises the South Santiam River downstream of Foster Dam to its confluence with the North Santiam River. The downstream boundary of this model is used as a tributary input to the North Santiam and Santiam River submodel.

- **North Santiam and Santiam River submodel:** Includes the North Santiam River from Big Cliff Dam to its confluence with the South Santiam River and the Santiam River to its confluence with the Willamette River. Outflow from the downstream boundary of this model is used as a tributary input to the Upper Willamette River submodel.

- **Upper Willamette River submodel:** Comprises the Willamette River from RM 185.3 near Eugene to RM 85.5 near Salem and receives inflows from the Coast Fork and Middle Fork Willamette River submodel at its upper end and from the McKenzie and Santiam River models as tributaries. Outflow from the downstream boundary of this model is used as upstream inflow to the Middle Willamette River submodel.

- **Middle Willamette River submodel:** Includes the Willamette River from RM 85.5 near Salem to RM 26.76 at Willamette Falls, along with two side branches that function in the model as alcoves at Wheatland Bar (RM 70.8) and Ash Island (RM 51.5).

The models included in this report were originally developed, calibrated, and documented in the early 2000s using CE-QUAL-W2 version 3.12 to simulate streamflow and stream temperature conditions in the Willamette River system for conditions that occurred in 2001 and 2002 (Berger and others 2004; Annear and others, 2004; Sullivan and Rounds, 2004; Bloom, 2016). The update from version 3.12 to version 4.2 represents approximately 13 years of accumulated "bug fixes," code improvements, and new and enhanced model capabilities. When using a model such as CE-QUAL-W2 that is under continuous development, it is wise to take advantage of improvements offered by newer versions. Although the version 3.12 models ran well and produced sufficiently accurate results when they were first used, version 4.2 of CE-QUAL-W2, with code enhancements added by USGS, represents a substantial improvement in model code and capability. The new capability in version 4.2 to run multiple submodels concurrently, rather than waiting for the upstream model to complete before starting the downstream model, represents a substantial potential decrease in total system model runtime and is reason enough to update these models to version 4.2. The models documented in this report represent a subset of the model domain initially developed to simulate conditions in 2001 and 2002 to provide a scientific basis for establishing a Total Daily Maximum Load (TMDL) for temperature in the Willamette River Basin. Other submodels developed for that TMDL, including models of the Long Tom River, Clackamas River, Willamette River downstream of Willamette Falls, and lower Columbia River, were beyond the scope of this study.

For this report, all submodels included in the 'river system model' were updated to CE-QUAL-W2, version 4.2 (Wells, 2019), with USGS modifications to allow heat tracking, and set up to simulate streamflow and temperature in model years 2011, 2015, and 2016 from about day-of-year (JDAY; after 'Julian day') 80 to JDAY 305, or about March 20/21 to October 31 or November 1, depending on leap years. Because these models were thoroughly documented as part of their initial development, documentation of model parameters in this report is limited to any changes in the models themselves, documentation of boundary condition data and estimates for the years modeled, and goodness-of-fit checks to ensure that the updated models adequately simulated the measured streamflow and temperature conditions for the new model years. The models themselves are publicly available at https://doi.org/10.5066/P908DXKH (Stratton Garvin and Rounds, 2021).

Locations and Reporting Units

Locations along the Willamette River and its tributaries are referenced using river miles (RMs), which begin at the mouth of each river and increase upstream. River miles are reported with high precision (for example, 38.94) to allow correlation with individual model segments. However, the reported river mile may not align perfectly with river mile locations in the real world. The river miles used in this report are calculated on the basis of the underlying model geometry and then compared with the original model documentation to most accurately align locations in the real world (for example, streamgaging stations) with the appropriate model location. Because the CE-QUAL-W2 model grid is somewhat simplified, particularly in multi-threaded river reaches, the reported river mile may not align perfectly with river mile locations reported by other sources. Other units of measurement presented in this report reflect those used by floodplain managers of the Willamette River Basin and include a blend of International System (SI) of Units and U.S. customary units with conversions presented in report front matter. Streamflow is given in cubic feet per second (ft^3/s) to align with the standard language used by dam operators, the original units reported by USGS streamgaging stations, and the streamflow requirements established in the Biological Opinion (National Marine Fisheries Service, 2008). All temperatures are given in degrees Celsius. The CE-QUAL-W2 model uses SI units; therefore, model dimensions are provided in their original SI units.

Report Structure

This report is structured to provide both generalized methods and detailed explanations of the updates and goodness-of-fits for each submodel. In the section "Methods and Data," a general overview of CE-QUAL-W2 and boundary conditions and updates common to all models is provided. The "Methods and Data" section also provides a general discussion of the various methods used to estimate streamflow or temperature conditions where data were unavailable to use as boundary conditions. Following "Methods and Data," the section "Model Updates" includes detailed descriptions of each submodel, including a description of the river reach and model domain, any updates to the bathymetric grid or other nontemporal parameters, temporal boundary conditions (meteorology, flow, and temperature), and updated goodness-of-fit performance statistics. The report concludes with a summary and suggestions for possible future research.

For more detailed information on CE-QUAL-W2 than is provided in this report, including discussion of heat budgets, readers are referred to the user manual for the model (Wells, 2019) and to previous Willamette River Basin stream temperature modeling reports (for example, Rounds, 2010). An overview of the basics of stream temperature dynamics and modeling can be found in Caissie (2006).

Methods and Data

Model Development

CE-QUAL-W2 is a two-dimensional hydrodynamic and water-quality model developed and jointly maintained by USACE and Portland State University that has been applied to a wide variety of rivers and reservoirs worldwide (Wells, 2019). CE-QUAL-W2 is a process-based mechanistic model, wherein streamflow is the result of a balance among inflows, structural features, and gravitational and frictional forces within the framework of a model grid representing river cross-sections along discrete reaches. Water temperature is simulated with a full heat budget that incorporates all incoming and outgoing environmental and advective energy fluxes as well as a detailed representation of topographic and vegetative shading (Wells, 2019). Because it is vertically and longitudinally discrete but assumes lateral homogeneity, CE-QUAL-W2 is most appropriate for long, narrow waterbodies (such as rivers and reservoirs) that may thermally stratify. While not optimized to model waterbodies with complex flows, such as hyporheic flows in interconnected and braided river channels, simple representations of features like reservoir arms or river side channels can be represented by interconnecting separate reaches of the model grid. The model runs at internally computed subdaily time steps and can be configured to simulate as long a time period as is computationally feasible. Output can be obtained at discrete locations and depths at specified dates or times of day, or for the entire model grid at specified intervals.

To run the model, CE-QUAL-W2 requires a ‘control file’ that specifies a wide range of model parameters, initial conditions, and links to other files containing necessary boundary conditions. In the following sections, an overview of non-temporal model parameters and boundary condition estimation techniques common to many models is provided. Updates to each submodel are then presented with an accompanying discussion of model goodness-of-fit statistics.

Updating of Model Parameters and Inputs

Model Grid and Structures

River bathymetry in the model grid is configured such that a river cross-section is represented by a series of stacked rectangles in which each ***layer*** has a defined width; the width typically increases in each layer from the riverbed to the river surface. Each cross-sectional representation is valid for a discrete model distance called a model ***segment***, and segments are connected longitudinally in the direction of flow to form a model ***branch***. A single, constant slope is applied to each branch, which commonly is zero (flat) for reservoirs and nonzero for sloping river reaches. Branches in CE-QUAL-W2 are connected via internal or external head or flow boundary conditions or by a specialized spillway or structure that controls the flow. Depending on the exact model configuration, internal flow boundary conditions can be specified using several types of structures (spillways, pipes, gates, etc.). The configuration of structures in the model is generally adapted to simulate actual hydraulic conditions (for example, the elevation of a spillway crest or the centerline elevation of a specific dam outlet structure); models may also include hypothetical structures to improve calibration and model stability by controlling flow. Branches in CE-QUAL-W2 are grouped into ***waterbodies***, which comprise the largest entity in the model grid and share groups of model inputs and parameters, such as meteorological inputs.

Only a few changes were made to the submodel grids, such as updates for the McKenzie River submodel and the Coast Fork and Middle Fork Willamette River submodel to take advantage of a new comma-delimited file format—a newer CE-QUAL-W2 capability that allows easier set-up and debugging. In addition, in the North Santiam and Santiam River and the Coast Fork and Middle Fork Willamette River submodels, changes to the model grid and model structures were made to improve model runtime and stability.

Specific changes to the model grid are discussed in the individual submodel sections of this report. In general, changes to the North Santiam and Santiam River and Coast Fork and Middle Fork Willamette River submodels were made to address model instabilities caused by the application of a single ***surface-layer index*** across dissimilar model branches. The surface-layer index is a waterbody-specific designation used by CE-QUAL-W2 as an internal reference point for many of its calculations. When running, CE-QUAL-W2 determines the model layer with the lowest water level in the waterbody, then uses that determination to assign a single surface-layer index to every segment in that waterbody. Water in layers in or above the designated surface layer is then handled by combining all of that water and its associated cross-sectional area into one active layer, regardless of the number of discrete layers of the model grid that may be occupied by the river above the surface layer in that segment at that time. Depending on the geometry of the model grid (in terms of branch slopes, branch boundaries, and waterbody groupings), it is possible for the river bottom in some segments to be higher in the model grid than the designated surface layer index for that particular waterbody. In such a case, the model can still run, but because of how water is grouped in layers above the surface-layer index, the model will represent any such segments one-dimensionally (rather than two-dimensionally, which would take advantage of the full capabilities of the model). This one-dimensional representation tends to cause model instabilities, which may cause the model to fail under certain flow conditions, as occurred in the North Santiam and Santiam River and Coast Fork and Middle Fork Willamette River submodels. To avoid this problem, the problematic waterbodies in the model domain were split into multiple waterbodies, allowing the waterbody-specific surface-layer index to be applied to fewer segments and decreasing the probability that some segments might be modeled one-dimensionally.

Hydraulic Parameters

CE-QUAL-W2 computes both bottom and vertical shear stress as part of its calculation of horizontal momentum, which is important in controlling the movement of water through the model. Specification of the Chezy or Manning's friction coefficient is a per-segment user input used in the calculation of frictional shear stress that can be adjusted as part of model calibration. Calculation of horizontal momentum also requires a specified vertical turbulence closure scheme. CE-QUAL-W2 can apply several different formulations for a vertical turbulence closure scheme, selected on a per-waterbody basis in the control file as the 'AZC' input. Formulations PARAB, NICK, and RNG are generally more appropriate for river models, as shear due to friction is dominant. The W2 or W2N formulations are generally more appropriate for flat-water models (reservoirs or lakes) where wind shear is dominant; however, the stability of the formulations vary (Cole and Wells, 2017). Efforts to improve the stability of several submodels included adjustments to both the Manning's friction coefficients and the turbulence closure schemes. Details of any changes to the friction coefficients or turbulence closure schemes are discussed in the individual submodel sections.

Shading

CE-QUAL-W2 applies both topographic and vegetative shade to the model. For the submodels included in this report, two estimates of shading parameters were originally developed (Annear and others, 2004; Sullivan and Rounds, 2004; Bloom, 2016). The "current conditions" shade parameters reflect estimated vegetative shading conditions in the early 2000s, based on a combination of GIS-based analysis and field surveys. The "system potential" shade parameters represent maximum estimated local shading potential based on the "current conditions" shade and an analysis of soil conditions, geology, ecoregions, geomorphic surfaces, historical records, some allowance for disturbance due to fire, and other factors. All submodels documented in this report utilize the current conditions shade parameters.

Boundary Conditions

CE-QUAL-W2 is data intensive, requiring temporal input for six or more meteorological parameters, flow and temperature for all inflows to the model (including to the upstream model boundary, from tributaries, and from point sources), and the flow rate for any withdrawals. Ideally, measured data would be available for all boundary conditions, but in practice, many boundary conditions must be estimated. Flow and temperature estimates for distributed tributaries, which approximate all ungaged flow in a branch and can be used to calibrate the water balance (or water budget) of the model, must also be provided. A wide range of data sources was used to provide measured or estimated boundary conditions to the models included in this report, as shown in table 1 and figure 2. All datasets were screened for outliers and missing values. Small gaps in datasets were generally interpolated, whereas larger gaps were filled using data from nearby and similar stations or with data from adjacent dates, as available and appropriate.

Meteorological data requirements for CE-QUAL-W2 include air temperature, dew-point temperature, wind speed, wind direction, solar radiation (optional, but used in all models in this report), and cloud cover. Air temperature, wind speed, and wind direction data are widely available from meteorological stations maintained at airports or other weather stations (National Centers for Environmental Information, 2020; Bureau of Reclamation, 2020; Western Regional Climate Center, 2020). When not reported directly, dew-point temperature can be estimated from air temperature and relative humidity. In some cases, the dew-point temperature was estimated using the 'weathermetrics' package in R, which applies algorithms from the National Weather Service's online heat index calculator (Anderson and others, 2016). Another method estimates dew-point temperature as:

$$T_{dp} = T_A - \frac{100 - RH}{5} \qquad \text{(1; Lawrence, 2005),}$$

where

T_{dp} is dew-point temperature, in degrees Celsius;
T_A is air temperature, in degrees Celsius; and
RH is relative humidity, in percent.

Table 1. Sources for all data input to the submodels documented in this report.

[Model use "supporting" indicates that data source was used to estimate a boundary condition. Web address or other citation information indicated in "Source" can be found in the report references. Map location numbers correspond to numbers on figure 2, organized roughly by agency, type, and latitude. "Temperature" refers to water temperature. **Abbreviations**: BOR, Bureau of Reclamation; EWEB, Eugene Water and Electric Board; WBAN, Weather-Bureau-Army-Navy, a weather station designation; NOAA, National Oceanic and Atmospheric Administration; NCEI, National Centers for Environmental Information; NWIS, U.S. Geological Survey National Water Information System; LCD, Local Climatological Data; ODEQ, Oregon Department of Environmental Quality; ODFW, Oregon Department of Fish and Wildlife; OWRD, Oregon Water Resources Department; PRIMET, Primary Meteorological (station); RAWS, Remote Automated Weather Station; SRML, Solar Radiation Monitoring Laboratory; USACE, U.S. Army Corps of Engineers; USEPA, U.S. Environmental Protection Agency; USGS, U.S. Geological Survey; LASAR, Laboratory Analytical Storage and Retrieval (database); AQWMS, Ambient Water Quality Monitoring System; ECHO, Environmental Compliance History Online; WWTP, Wastewater Treatment Plant; —, no map number.]

Data type	Monitoring station	Model use	Agency	Source	Map location
Temperature	City of Salem at Geren Island, North Santiam River	Calibration	City of Salem	*Written commun., 2016	70
Flow (withdrawal)	City of Salem water intake at Geren Island, North Santiam River	Boundary condition	City of Salem	*Written commun., 2016	70
Temperature	LASAR 10363, Yamhill River	Supporting	ODEQ	LASAR (discontinued)	82
Temperature	LASAR 10783, Thomas Creek	Supporting	ODEQ	LASAR (discontinued)	79
Temperature	LASAR 10784, Crabtree Creek	Supporting	ODEQ	LASAR (discontinued)	78
Temperature	LASAR 11102, Rickreall Creek	Supporting	ODEQ	LASAR (discontinued)	81
Temperature	LASAR 11182, Calapooia River	Supporting	ODEQ	LASAR (discontinued)	75
Temperature	LASAR 11419, Hamilton Creek	Supporting	ODEQ	LASAR (discontinued)	77
Temperature	LASAR 23778, McDowell Creek	Supporting	ODEQ	LASAR (discontinued)	76
Temperature	LASAR 28108, Bear Creek	Supporting	ODEQ	**Written commun., 2019	73
Temperature	LASAR 28115, Finn Creek	Supporting	ODEQ	**Written commun., 2019	74
Temperature	LASAR 28144, Deer Creek	Supporting	ODEQ	**Written commun., 2019	72
Temperature	LASAR 32059, Molalla River	Supporting	ODEQ	LASAR (discontinued)	83
Temperature	LASAR site 10658, Luckiamute River	Supporting	ODEQ	LASAR (discontinued)	80
Flow (withdrawal)	Leaburg Canal	Boundary condition	EWEB	***Written commun., 2019	67
Flow, temperature	Mill Creek 3, Mill Creek at North Salem High School	Boundary condition	City of Salem	*Written commun., 2016	71
Flow (withdrawal)	Sweet Home Canal	Boundary condition	OWRD	Water use report	69
Flow	USACE EUGO3	Calibration	USACE	DataQuery 2.0	8
Flow, temperature	USGS 14156500, Mosby Creek (historical)	Supporting	USGS	NWIS	6
Flow, temperature	USGS 14197900, Willamette River at Newberg	Calibration	USGS	NWIS	47
Flow (estimated), temperature (estimated)	USGS 444113123001900, South Santiam River at RM 0.1 near Jefferson	Calibration	USGS	USGS Data Grapher	52
Flow, temperature	USGS 14150000, Middle Fork Willamette River near Dexter	Boundary condition	USGS	NWIS	1

Table 1. Sources for all data input to the submodels documented in this report. —Continued

[Model use "supporting" indicates that data source was used to estimate a boundary condition. Web address or other citation information indicated in "Source" can be found in the report references. Map location numbers correspond to numbers on figure 2, organized roughly by agency, type, and latitude. "Temperature" refers to water temperature. **Abbreviations**: BOR, Bureau of Reclamation; EWEB, Eugene Water and Electric Board; WBAN, Weather-Bureau-Army-Navy, a weather station designation; NOAA, National Oceanic and Atmospheric Administration; NCEI, National Centers for Environmental Information; NWIS, U.S. Geological Survey National Water Information System; LCD, Local Climatological Data; ODEQ, Oregon Department of Environmental Quality; ODFW, Oregon Department of Fish and Wildlife; OWRD, Oregon Water Resources Department; PRIMET, Primary Meteorological (station); RAWS, Remote Automated Weather Station; SRML, Solar Radiation Monitoring Laboratory; USACE, U.S. Army Corps of Engineers; USEPA, U.S. Environmental Protection Agency; USGS, U.S. Geological Survey; LASAR, Laboratory Analytical Storage and Retrieval (database); AQWMS, Ambient Water Quality Monitoring System; ECHO, Environmental Compliance History Online; WWTP, Wastewater Treatment Plant; —, no map number.]

Data type	Monitoring station	Model use	Agency	Source	Map location
Flow, temperature	USGS 14151000, Fall Creek below Winberry Creek	Boundary condition	USGS	NWIS	2
Flow, temperature	USGS 14152000, Middle Fork Willamette River near Jasper	Supporting; calibration	USGS	NWIS	3
Flow, temperature	USGS 14153500, Coast Fork Willamette River below Cottage Grove	Boundary condition	USGS	NWIS	4
Flow, temperature	USGS 14155500, Row River near Cottage Grove	Boundary condition	USGS	NWIS	5
Flow	USGS 14157500, Coast Fork Willamette River near Goshen	Calibration	USGS	NWIS	7
Temperature	USGS 14158100, Willamette River at Owosso Bridge	Calibration	USGS	NWIS	8
Flow	USGS 14159000, McKenzie River at McKenzie Bridge	Supporting	USGS	NWIS	9
Temperature	USGS 14159110, McKenzie River above South Fork near Rainbow	Supporting	USGS	USGS Data Grapher	10
Temperature	USGS 14159200, South Fork McKenzie River above Cougar Lake	Supporting	USGS	NWIS	11
Flow, temperature	USGS 14159500, South Fork McKenzie River below Cougar Dam	Boundary condition	USGS	NWIS	12
Flow, temperature	USGS 14162200, Blue River at Blue River	Boundary condition	USGS	NWIS	13
Flow, temperature	USGS 14162500, McKenzie River near Vida	Calibration	USGS	NWIS	14
Flow	USGS 14163150, McKenzie River below Leaburg Dam	Calibration	USGS	NWIS	15
Flow	USGS 14163900, McKenzie River near Walterville	Calibration	USGS	NWIS	16
Temperature	USGS 14164550, Camp Creek at Camp Creek Road Bridge near Springfield	Supporting	USGS	NWIS	17
Flow, temperature	USGS 14164900, McKenzie River above Hayden Bridge	Calibration	USGS	NWIS	18

Table 1. Sources for all data input to the submodels documented in this report. —Continued

[Model use "supporting" indicates that data source was used to estimate a boundary condition. Web address or other citation information indicated in "Source" can be found in the report references. Map location numbers correspond to numbers on figure 2, organized roughly by agency, type, and latitude. "Temperature" refers to water temperature. **Abbreviations**: BOR, Bureau of Reclamation; EWEB, Eugene Water and Electric Board; WBAN, Weather-Bureau-Army-Navy, a weather station designation; NOAA, National Oceanic and Atmospheric Administration; NCEI, National Centers for Environmental Information; NWIS, U.S. Geological Survey National Water Information System; LCD, Local Climatological Data; ODEQ, Oregon Department of Environmental Quality; ODFW, Oregon Department of Fish and Wildlife; OWRD, Oregon Water Resources Department; PRIMET, Primary Meteorological (station); RAWS, Remote Automated Weather Station; SRML, Solar Radiation Monitoring Laboratory; USACE, U.S. Army Corps of Engineers; USEPA, U.S. Environmental Protection Agency; USGS, U.S. Geological Survey; LASAR, Laboratory Analytical Storage and Retrieval (database); AQWMS, Ambient Water Quality Monitoring System; ECHO, Environmental Compliance History Online; WWTP, Wastewater Treatment Plant; —, no map number.]

Data type	Monitoring station	Model use	Agency	Source	Map location
Flow, temperature	USGS 14165000, Mohawk River near Springfield	Boundary condition; supporting	USGS	Flow from NWIS; temperature available from USGS Data Grapher	19
Flow	USGS 14165500, McKenzie River near Coburg	Supporting; calibration	USGS	NWIS	20
Flow, temperature	USGS 14166000, Willamette River at Harrisburg	Calibration	USGS	NWIS	21
Flow	USGS 14170000, Long Tom River at Monroe	Boundary condition	USGS	NWIS	22
Flow	USGS 14171000, Marys River near Philomath	Boundary condition	USGS	NWIS	23
Flow	USGS 14173500, Calapooia River at Albany	Supporting	USGS	NWIS	24
Flow, temperature	USGS 14174000, Willamette River at Albany	Calibration	USGS	NWIS	25
Flow, temperature	USGS 14181500, North Santiam River at Niagara	Boundary condition	USGS	NWIS	26
Flow	USGS 14181750, Rock Creek near Mill City	Supporting	USGS	NWIS	27
Flow, temperature	USGS 14182500, Little North Santiam River near Mehama	Boundary condition; supporting; proxy record	USGS	NWIS	28
Flow	USGS 14183000, North Santiam River at Mehama	Calibration	USGS	NWIS	29
Temperature	USGS 14183010, North Santiam River near Mehama	Calibration	USGS	NWIS	30
Flow	USGS 14184100, North Santiam River at Greens Bridge	Calibration	USGS	NWIS	31
Temperature	USGS 14185000, South Santiam River below Cascadia	Proxy boundary condition	USGS	NWIS	32
Temperature	USGS 14185900, Quartzville Creek near Cascadia	Supporting	USGS	NWIS	33
Flow	USGS 14187000, Wiley Creek near Foster	Boundary condition	USGS	NWIS	34
Flow	USGS 14187200, South Santiam River near Foster	Boundary condition	USGS	NWIS	35

Table 1. Sources for all data input to the submodels documented in this report. —Continued

[Model use "supporting" indicates that data source was used to estimate a boundary condition. Web address or other citation information indicated in "Source" can be found in the report references. Map location numbers correspond to numbers on figure 2, organized roughly by agency, type, and latitude. "Temperature" refers to water temperature. **Abbreviations**: BOR, Bureau of Reclamation; EWEB, Eugene Water and Electric Board; WBAN, Weather-Bureau-Army-Navy, a weather station designation; NOAA, National Oceanic and Atmospheric Administration; NCEI, National Centers for Environmental Information; NWIS, U.S. Geological Survey National Water Information System; LCD, Local Climatological Data; ODEQ, Oregon Department of Environmental Quality; ODFW, Oregon Department of Fish and Wildlife; OWRD, Oregon Water Resources Department; PRIMET, Primary Meteorological (station); RAWS, Remote Automated Weather Station; SRML, Solar Radiation Monitoring Laboratory; USACE, U.S. Army Corps of Engineers; USEPA, U.S. Environmental Protection Agency; USGS, U.S. Geological Survey; LASAR, Laboratory Analytical Storage and Retrieval (database); AQWMS, Ambient Water Quality Monitoring System; ECHO, Environmental Compliance History Online; WWTP, Wastewater Treatment Plant; —, no map number.]

Data type	Monitoring station	Model use	Agency	Source	Map location
Flow	USGS 14187500, South Santiam River at Waterloo	Calibration	USGS	NWIS	36
Flow (withdrawal)	USGS 14187600, Lebanon Santiam Canal near Lebanon	Boundary condition	USGS	NWIS	37
Flow	USGS 14188700, Crabtree Creek near Crabtree	Supporting	USGS	NWIS	38
Flow	USGS 14188800, Thomas Creek near Scio	Boundary condition	USGS	NWIS	39
Flow	USGS 14189000, Santiam River at Jefferson	Calibration	USGS	NWIS	40
Temperature	USGS 14189050, Santiam River near Jefferson	Calibration	USGS	NWIS	41
Flow	USGS 14190500, Luckiamute River near Suver	Boundary condition	USGS	NWIS	42
Flow	USGS 14191000, Willamette River at Salem	Calibration	USGS	NWIS	43
Temperature	USGS 14192015, Willamette River at Keizer	Supporting; calibration	USGS	NWIS	44
Temperature	USGS 14192500, South Yamhill River near Willamina	Supporting	USGS	NWIS	45
Flow	USGS 14194150, South Yamhill River at McMinnville	Supporting	USGS	NWIS	46
Flow	USGS 14200000, Molalla River near Canby	Supporting	USGS	NWIS	48
Flow	USGS 14202000, Pudding River at Aurora	Supporting	USGS	NWIS	49
Flow, temperature	USGS 14207200, Tualatin River at Oswego Dam	Boundary condition	USGS	NWIS	50
Temperature	USGS 14211550, Johnson Creek at Milwaukie	Supporting	USGS	NWIS	51
Temperature	USGS 14318000, Little River at Peel	Proxy boundary condition	USGS	NWIS	—
Temperature	USGS 453004122510301, Beaverton Creek at 170th Ave, Beaverton	Supporting	USGS	NWIS	53
Temperature	USGS 453040123065201, Gales Creek at old Highway 47, Forest Grove	Supporting	USGS	NWIS	54

Table 1. Sources for all data input to the submodels documented in this report. —Continued

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Data type	Monitoring station	Model use	Agency	Source	Map location
Flow (withdrawal)	Walterville Canal Flow	Boundary condition	EWEB	***Written commun., 2019	68
Temperature	Willamette Falls fish ladder	Calibration	ODFW	****Written commun., 2020	84
Meteorological	Agrimet Corvallis	Boundary condition	BOR	Agrimet	94
Meteorological	Aurora State Airport (WBAN 94281)	Boundary condition	NOAA	NCEI LCD	87
Meteorological	Corvallis Municipal Airport (WBAN 24202)	Boundary condition	NOAA	NCEI LCD	86
Meteorological	Eugene Airport (Mahlon Sweet Field) (WBAN 24221)	Boundary condition	NOAA	NCEI LCD	85
Meteorological	H.J. Andrews PRIMET	Boundary condition	H.J. Andrews Research Forest	H.J. Andrews Research Forest	91
Meteorological	McMinnville Municipal Airport (WBAN 94273)	Boundary condition	NOAA	NCEI LCD	93
Meteorological	RAWS High Point	Boundary condition	Western Regional Climate Center	RAWS	88
Meteorological	RAWS Jordan	Boundary condition	Western Regional Climate Center	RAWS	90
Meteorological	RAWS Trout Creek	Boundary condition	Western Regional Climate Center	RAWS	89
Meteorological	Salem Municipal Airport (McNary Field) (WBAN 24232)	Boundary condition	NOAA	NCEI LCD	92
Meteorological	University of Oregon Solar Radiation Monitoring Laboratory - Eugene	Boundary condition	University of Oregon SRML	University of Oregon SRML	95
Meteorological	University of Oregon Solar Radiation Monitoring Laboratory - Portland	Boundary condition	University of Oregon SRML	University of Oregon SRML	96
Point source	Canby WWTP	Boundary condition	ODEQ	*****Written commun., 2016	65
Point source	City of Cottage Grove WWTP	Boundary condition	USEPA	ECHO	55
Point source	International Paper Springfield	Boundary condition	ODEQ	*****Written commun., 2016	56
Point source	Jefferson WWTP	Boundary condition	2001 model	Annear and others (2004)	60
Point source	Lebanon WWTP	Boundary condition	ODEQ	*****Written commun., 2016	58
Point source	Salem WWTP	Boundary condition	ODEQ	*****Written commun., 2016	62

Table 1. Sources for all data input to the submodels documented in this report. —Continued

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Data type	Monitoring station	Model use	Agency	Source	Map location
Point source	SP Newsprint, Newberg	Boundary condition	2001 model values; zeroed 2015	Annear and others (2004)	63
Point source	Stayton WWTP	Boundary condition	2001 model	Annear and others (2004)	59
Point source	Sweet Home WWTP	Boundary condition	2001 model	Annear and others (2004)	57
Point source	Wah Chang/ATI/Albany WWTP	Boundary condition	ODEQ	*****Written commun., 2016	61
Point source	West Linn WWTP	Boundary condition	ODEQ	*****Written commun., 2016	66
Point source	Wilsonville WWTP	Boundary condition	ODEQ	*****Written commun., 2016	64

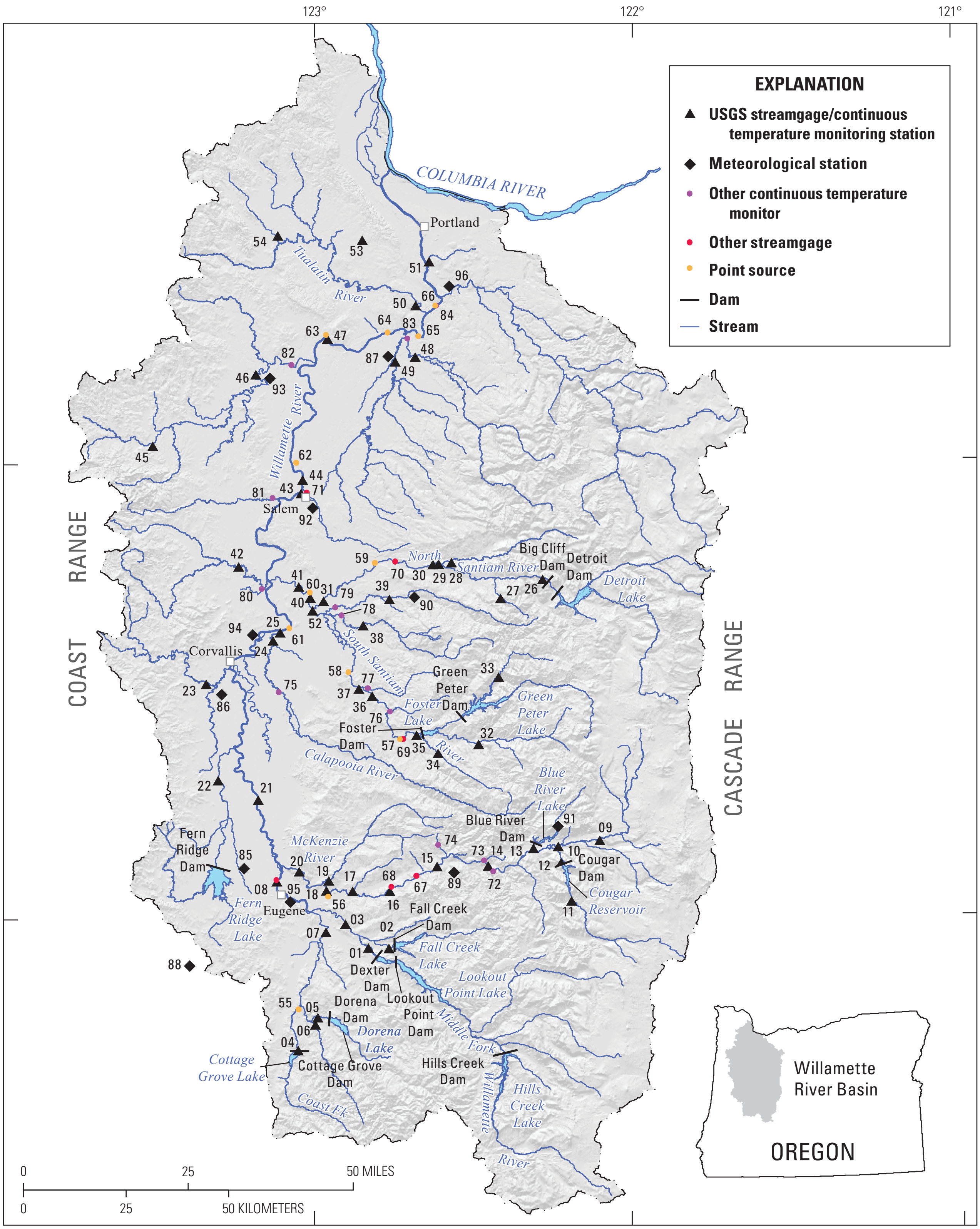
*J. Boyington and T. Sherman, City of Salem, written commun., 2016

**D. Brown, Oregon Department of Environmental Quality, written commun., 2019

***M. Zinniker, D. Donahue, and K. Morgenstern, Eugene Water and Electric Board, written commun., 2019

****K. Melchar, Oregon Department of Fish and Wildlife, written commun., 2020

*****S. Schnurbush, Oregon Department of Environmental Quality, written commun., 2016



Base map modified from U.S. Geological Survey and other digital data sets (1:2,000,000; 1:100,000).
Projection: Oregon Lambert Conformal Conic, NAD 83, NAVD 88.

Figure 2. Location of all data sources used in updating the models. Numbers correspond to the data sources listed in table 1. U.S. Geological Survey (USGS) station 14318000, Little River at Peel (not mapped), is beyond the southern boundary of the Willamette River Basin at 43°15′10″, 123°01′30″ (North American Datum of 1927).

Cloud cover in CE-QUAL-W2 utilizes a dimensionless scale from 0 to 10, where 0 indicates no clouds and 10 indicates complete cloud cover. Where incident solar radiation data are available, cloud cover can be estimated by calculating the difference between measured and theoretical incident solar radiation (the solar radiation at the Earth's surface; Wells, 2019). This method has been successfully applied to Willamette River system submodels in the past (for example, Bloom, 2016); however, it requires that night-time cloud cover be interpolated. An alternative method, where available, is to use cloud cover reports from nearby airports. Airport cloud cover is typically reported on the hour in eighths, or 'oktas,' where 00 indicates 'clear,' 01-02 indicates 'few' clouds, 03-04 indicates 'scattered' clouds, 05-07 indicates 'broken' clouds, and 08 indicates 'overcast' (09 and 10 indicate obscuration due to fog, smoke, or other causes) (National Centers for Environmental Information Web Services, 2020). To convert reported oktas to the scale utilized by CE-QUAL-W2, the following conversion was applied:

- 00 oktas (clear) = 0
- 01-02 oktas (few clouds) = 1.5
- 03-04 oktas (scattered clouds) = 3.8
- 05-07 oktas (broken clouds) = 6.9
- 08, 09, 10 oktas (obscured, portion obscured) = 10

Both methods were used in updates to the submodels in this report, depending on how the original model was calibrated and the relative accuracy of the resulting model fit.

Solar radiation data were available from the University of Oregon Solar Radiation Monitoring Laboratory (University of Oregon, 2020), the H.J. Andrews Primary Meteorological (PRIMET) weather station (HJ Andrews Experimental Forest Long-Term Ecological Research Network, 2020), and some automated agricultural weather stations (Agrimet; Bureau of Reclamation, 2020). Reported values are global (the sum of direct, diffuse, and ground-reflected values) and were converted from langleys per hour to watts per square meter.

Precipitation can be included in CE-QUAL-W2, which may be important for waterbodies with large surface areas, such as lakes and reservoirs; however, direct precipitation was not included in any of the submodels documented in this report. Any such direct precipitation was instead included in the distributed tributary model inputs that account for any ungaged water inputs and withdrawals.

Boundary conditions associated with direct inputs or withdrawals in these models include streamflow, stream temperature, discharges and temperatures from point sources, and withdrawal rates. Most of the streamflow and water temperature data used in the models were collected at continuous monitoring stations maintained by the USGS and accessed via the National Water Information System (NWIS; U.S. Geological Survey, 2020a). A few streamflow records were obtained from the USACE Dataquery website (U.S. Army Corps of Engineers, 2020) or from the USGS Data Grapher (U.S. Geological Survey, 2020b). Additionally, data from the Oregon Department of Environmental Quality (ODEQ) legacy Laboratory Analytical Storage and Retrieval (LASAR) database were used to help estimate some stream temperatures. As of 2019, LASAR had been retired and replaced by the Ambient Water Quality Monitoring System (AWQMS), but subdaily data had not yet been transferred. Some subdaily data were requested and made available directly from ODEQ (D. Brown, Oregon Department of Environmental Quality, written commun., 2019; Oregon Department of Environmental Quality, 2020a).

Point sources generally include municipal wastewater treatment plants and industrial facilities that discharge into surface waters. These facilities are required to have a National Pollutant Discharge Elimination System (NPDES) permit under the federal Clean Water Act (Public Law 92–500, 33 U.S.C. §1251 et seq. [1972]). Compliance requires monitoring and reporting discharge rates and water-quality parameters; these data are available from ODEQ (S. Schnurbush, Oregon Department of Environmental Quality, written commun., 2016) or the U.S. Environmental Protection Agency (USEPA) Enforcement and Compliance History Online (ECHO) database (U.S. Environmental Protection Agency, 2020). For years in which updated point-source discharge and temperature data were unavailable, data from the closest year were applied.

Most withdrawal rates were estimated to be identical to those from the original models. Updated withdrawal rates for the City of Salem's water intake on the North Santiam River near Stayton, and the Eugene Water and Electric Board canal diversions from the McKenzie River, were provided by the respective agencies (J. Boyington and T. Sherman, City of Salem, written commun., 2016; M. Zinniker, D. Donahue, and K. Morgenstern, Eugene Water and Electric Board, written commun., 2019). Many withdrawals were included in the original submodels as "travel-time offsets" for point-source discharges. These are artificial withdrawals immediately upstream of a corresponding point source that remove the same volume of water as that added by the real point source. These travel-time offsets are artifacts of previous analyses to determine the cumulative effect of point source discharges to spatial patterns of daily maximum water temperatures in the Willamette River network. Without travel-time offsets, the shifting spatial patterns of daily maximum temperatures caused by small changes in streamflow made a comparison of with-point-source model results to without-point-source model results unnecessarily complicated; the reasoning behind these offsets was documented in more detail by Rounds (2007). Withdrawals are specified as discharge only; the model removes the specified withdrawal flow at the temperature of the model cell specified by the withdrawal's elevation.

Boundary Condition Estimation Methods

Inputs were estimated where flow and temperature data were unavailable for boundary inputs to the model. In many cases, estimation methods were established in the initial development of the submodels. The updated models used many of the same techniques that had been previously established, except when alternatives produced a time series with a closer fit to existing data. Where historical data are available, a time series for the period of interest can be developed by correlating historical data with another dataset that overlaps both the historical time series and the period of interest. Where no historical data are available, alternative methods must be developed.

Three methods for estimating streamflow were utilized in the model updates. Where historical data were available, a regression between the historical data and overlapping data from another continuous record was developed. For example, flow in Mosby Creek (a tributary to the Row River) was estimated using a logarithmic regression with flow in the Row River above Dorena Lake, which yielded an estimate of streamflow in Mosby Creek with an R^2 value of 0.97 (see equation 2 and associated discussion for more details). Alternatively, streamgaging station records could be adjusted using simple arithmetic. For example, Wiley Creek enters the South Santiam River upstream of the upstream-most streamgaging station in the model domain. The boundary condition for flow into the South Santiam River submodel was thus estimated by subtracting the measured streamflow for Wiley Creek from the measured streamflow at the South Santiam River streamgaging station near Foster Dam. In many cases, no measured streamflow data (historical or current) were available. In these cases, a watershed area ratio method was used. In its simplest form, the watershed area ratio method estimates a streamflow time series for an ungaged basin by weighting a nearby streamflow record according to the ratios between the two basins' watershed areas (for example, see equation 18; Emerson and others, 2005).

In the McKenzie River Basin, a more complex "weighted watershed area ratio method" had to be employed to estimate streamflow. The McKenzie River submodel has many tributaries without streamgaging station records and with complex hydrologic conditions influenced by the Leaburg and Walterville Canals. To produce streamflow estimates for these tributaries, Annear and others (2004) divided the McKenzie River submodel into four reaches, demarcated by the location of streamgaging stations at the upstream and downstream boundaries. Within each reach, ungaged flow was calculated by comparing the difference between the streamflows at the upstream and downstream streamgaging stations (accounting for the influence of Leaburg and Walterville Canals, as necessary). This ungaged flow was then apportioned between ungaged tributaries according to the ratio between the tributary watershed area and the total ungaged watershed area contributing to the reach. Annear and others (2004) assigned this ungaged flow in each reach to an artificial tributary acting in each reach instead of using distributed tributaries to adjust the water balance; however, a different approach was utilized in this model update. For more details, see section "Model Updates: McKenzie River Submodel: Temporal Inputs: Flow."

Estimated temperature time series required for the submodel updates were produced either with regression methods or by applying a proxy record. Where historical records were available, water temperature time series were estimated using either simple linear regression with data from a nearby monitoring station or using multiple linear regression and a stepwise algorithm to identify the best regression among many potential data sources with the Akaike Information Criterion (AIC) as a decision factor (see Venables and Ripley, 2002). The final estimation method was generally selected among several options, depending on the regression model goodness-of-fit statistics or the estimated time series that most improved the temperature fit in the CE-QUAL-W2 submodel. Where no current or historical data were available to develop a correlation-based estimated time series, water temperature records were estimated using a proxy record from a nearby monitoring station. The most appropriate proxy was selected on the basis of proximity and similarities in drainage area, aspect, and geology (for example, High Cascades versus Western Cascades geologic province, see Callaghan and Buddington, 1938; Tague and Grant, 2004; and Jefferson and others, 2006). Often, several options were tested and the proxy record which produced the best CE-QUAL-W2 model fit was selected.

Many of the water temperature estimates documented in this report are derived from continuous temperature records from monitoring stations that were installed and operated in the early 2000s to support the initial development of the models in this report (stations from the Oregon Department of Environmental Quality labelled "LASAR"; table 1). These data are generally limited to May through October, while the models here span late March through October. Because of the paucity of data from these LASAR monitoring stations in March and April, water temperature estimates made using the LASAR data are subject to greater uncertainty in the early spring.

Model calibration

Because all models updated in this report had been previously calibrated and documented, the term 'calibration' as used in this report refers generally to the estimation and application of distributed tributary flows to achieve a balanced water budget and an iterative analysis of model simulation results to determine the best data sources or estimation methods for boundary conditions in 2011, 2015, and 2016. Model accuracy was assessed at locations within each model domain where continuous data were available for the years simulated. Compared to the data available for the 2001 and 2002 models, for which continuous datasets were collected at many points in the modeling domain specifically to support the modeling effort, fewer water temperature data were available to check these model updates. Plots of the water balance and temperature fit, along with goodness-of-fit statistics, are provided later in this report in the discussion of each submodel.

The water balance for each submodel was developed iteratively, from upstream to downstream, by adjusting flows in the distributed tributaries of branches upstream of the upstream-most streamgaging station and moving downstream until the modeled flow generally matched that of all available data locations. A distributed tributary is a model input meant to account for all ungaged flow inputs (including precipitation) and withdrawals in a model branch. Distributed tributary flow can be positive (indicating input, or gain, to the model) or negative (indicating withdrawal, or loss, from the model) and is spread out over every segment in the specified branch (as opposed to tributaries, which direct flow into a specific segment). To calibrate the water balance in each submodel, distributed tributaries were activated but initially set to zero flow. The difference in flow as calculated by the model and as measured at a streamgaging station was then applied to branches upstream of the streamgaging station and split, as necessary, among any relevant model branches. Distributed tributary flows typically were estimated with one value for each day, and often were smoothed to remove any travel-time artifacts. Distributed tributaries account for both ungaged surface flow as well as groundwater flow, which tends not to vary on a subdaily time scale. Additionally, because flow in distributed tributaries is spread among all segments within a model branch, a subdaily time step can introduce travel-time errors into the water balance. The model was then re-run with the updated distributed tributaries and the process repeated until the closest reasonable water balance was achieved, as determined by comparing time series of measured and modeled streamflow. Because streamgaging station locations do not necessarily coincide with branch boundaries, some judgement was required to determine the branches to which a particular distributed tributary was applied. The presence of small, ungaged tributaries or previous studies identifying losing or gaining stream reaches could occasionally guide these decisions. More details and any deviation from this approach are discussed later in the appropriate submodel section.

Because all the submodels described in this report were previously developed, calibrated, and documented, efforts to achieve the best temperature fit for the updated submodels were limited to modifications of boundary condition sources, proxy locations, or methods used to estimate boundary conditions where data were not available; or to the minor adjustment of model parameters to improve stability or fit. A comprehensive effort to improve the model bathymetry or other parameters was beyond the scope of this study. The model fit for water temperature was evaluated by plotting modeled subdaily, daily maximum, and daily minimum temperatures against measured data, where available, and by evaluating goodness-of-fit statistics, including the mean error (ME), mean absolute error (MAE), and root mean squared error (RMSE).

Model Updates

Coast Fork and Middle Fork Willamette River Submodel

Reach Description

The Coast Fork and Middle Fork Willamette River submodel consists of the uppermost 2 miles of the Willamette River, near Eugene, and four upstream tributaries with outflows from USACE dams in the southernmost part of the Willamette River Basin. The drainage basin represented by the model encompasses an area of approximately 2,040 mi^2 and receives approximately 61 inches of precipitation annually (U.S. Geological Survey, 2020c).

The Middle Fork Willamette River drains the foothills and upper elevations of the Cascade Range (Branscomb and others, 2002). Most of its upper reaches are in the High Cascades geologic province, which is highly permeable and consequently has many large spring complexes that feed the headwater streams. Upstream USACE dams include Fall Creek Dam on Fall Creek and Dexter, Lookout Point, and Hills Creek Dams on the Middle Fork Willamette River. Of the tributaries included in the Coast Fork and Middle Fork Willamette River submodel, the Middle Fork Willamette River has the largest drainage basin (approximately 1,379 mi^2) and the largest mean annual streamflow (4,080 ft^3/s), as measured at the USGS streamgaging station at Jasper (station 14152000; U.S. Geological Survey, 2020c). Fall Creek is a tributary to the Middle Fork Willamette River that drains an area of 252 mi^2 in the lower elevations of the Cascade Range foothills and, with a mean annual streamflow of 575 ft^3/s as measured at USGS streamgaging station 14151000, is the smallest of the tributaries included within the model domain.

The Coast Fork Willamette River joins the Middle Fork Willamette River to form the Willamette River upstream of Eugene. It drains approximately 667 mi^2 of the eastern Coast Range and westernmost Cascade Range (Branscomb and others, 2002; U.S. Geological Survey, 2020c). The Coast Fork Willamette River is dammed by Cottage Grove Dam upstream of Cottage Grove, Oregon. With an average annual streamflow of 1,550 ft^3/s, as measured at the USGS streamgaging station near Goshen (station 14157500), the Coast Fork Willamette River is the second largest of the tributaries included in the Coast Fork and Middle Fork Willamette River submodel. The largest tributary of the Coast Fork Willamette River is the Row River, a stream with a mean annual discharge of 735 ft^3/s downstream of Dorena Dam as measured at the USGS streamgaging station near Cottage Grove (station 14155500).

Model Domain

The Coast Fork and Middle Fork Willamette River submodel was originally developed by Portland State University for conditions occurring spring through autumn in 2001 and

2002 (Annear and others, 2004; Berger and others, 2004). As modified for 2011, 2015, and 2016, the model comprises eight waterbodies and 12 branches (fig. 3). The Coast Fork Willamette River is modeled as branches 1 through 4. The Row River is modeled as branches 5 through 8, joining the Coast Fork Willamette River in branch 2 at segment 61. The Middle Fork Willamette River is modeled as branches 9 and 10. Fall Creek (branch 11) discharges to the Middle Fork Willamette River in branch 10 at segment 288. The Coast Fork Willamette River (branch 4) enters the Middle Fork Willamette River in branch 10 at segment 358. Branch 10 flows into branch 12 at segment 409 to form the main-stem Willamette River. Waterbodies 1-4 correspond to branches 1-4 (Coast Fork Willamette River). Waterbody 5 includes branches 5–8 (Row River). Waterbody 6 includes branches 9 and 10 (Middle Fork Willamette River). Waterbody 7 includes branch 11 (Fall Creek), and waterbody 8 includes branch 12 (Willamette River).

Flow boundary conditions into the submodel include inflow to four branches (the Row, Coast Fork Willamette, and Middle Fork Willamette Rivers, and Fall Creek), one tributary, one point source, and five distributed tributaries. One withdrawal is included in the submodel as a travel-time offset for the point source.

Bathymetric Grid and Non-Temporal Parameters

To address a number of model instabilities and undesirable oscillations in flow when the model was upgraded to version 4.2 for years 2011, 2015, and 2016, several changes were made to the model grid. As originally built, the Coast Fork and Middle Fork Willamette River submodel was configured with five waterbodies, 10 branches, and 4 spillways. In the updated version, the model was reconfigured into 8 waterbodies with 12 branches and 7 spillways. The first two branches in the first waterbody of the original model, representing the Coast Fork Willamette River, were split into 4 branches with each branch in its own waterbody. By putting each of these branches into its own waterbody, the model was allowed to use a different surface-layer index (a model designation used as a reference point for many calculations and assigned on a waterbody basis; see section “Methods and Data: Updating of Model Parameters and Inputs: Model Grid and Structures” for more detailed discussion) for each branch. This change allowed the model to represent the river in multiple active layers rather than as one surface layer and helped to eliminate some model instabilities. Additionally, model spillways were added at several branch connections and a few of the existing model spillway crest elevations were increased slightly, which helped to eliminate some model instabilities by changing those branch connections from a water-surface elevation boundary condition to a flow boundary condition and making the flows more stable. Sometimes a spillway might be added to a model in an attempt to simulate a pool/riffle feature that is not captured by the coarseness of the model grid, or a model spillway might be added to better control water flow and increase model stability without actually creating any substantive pooling in the model; the latter reason was the case here, to make the model more stable. Lastly, in an attempt to decrease any large differences in cell width between adjacent layers in the grid, layers 26-44 of the original model (the lowest 19 active layers, each 1.0 meter, m, tall) were split in half vertically to create layers 26-63 of the new model (38 layers, each 0.5 m tall), with cell widths adjusted to preserve the volume of the original grid. Large width differences between adjacent layers of the same segment can lead to large changes in frictional shear stress when an increase or decrease in water depth from one time step to the next causes the water surface to rise into a wider cell or recede into a narrower cell in the grid; such discontinuities in width and shear stress can cause model instabilities and oscillations in the computed water-surface elevation and flow.

In addition to the structural changes to the model, the initial water-surface elevation and some friction coefficients were adjusted to further improve its stability. The initial water-surface elevation specified in the original model was decreased by at least 1.5 m in each segment. This change was helpful in two ways. First, even with a lower initial water-surface elevation, the model had an excess of water in the model grid relative to the amount of flow moving through the system on the first day of the simulation. As is typical in these models, the first day (or so) of the simulation is one in which an initially stagnant pool of water begins moving downstream and establishing a set of downstream velocities and water levels in each segment that are consistent with the incoming flows from upstream boundaries and tributaries. When the initial water-surface elevations are higher than necessary, the model must “drain” a large amount of excess water out of the model grid, discharging higher-than-normal simulated flows in the first hours of the simulation. Sometimes, the movement of large amounts of water in the early part of a simulation can lead to model instabilities and even cause the model to crash. Decreasing the initial water-surface elevations by 1.5 m (and 2.0 m in a few segments of the upper Row River) was helpful in decreasing the amount of water that had to drain out of the grid in the first day of the simulation, and also eliminated some problematic instabilities. In addition, the start date of the model simulation was decreased by one day to allow for the excess water to drain out of the model grid before the start date of downstream models, so that the excess initial water from this model did not have to be transported through the downstream models. Finally, the Manning’s friction coefficients in several segments were modified to increase model stability. Friction coefficients were decreased in some of the upstream segments of the Coast Fork Willamette River and increased slightly in all segments of the uppermost branch of the Row River. A decrease in a friction coefficient allows the water to move through a narrow river section more quickly, whereas a greater friction coefficient results in slightly increased water depths. These changes were made iteratively and in response to conditions that were causing model instabilities. The modified friction coefficients were helpful in eliminating those instabilities.

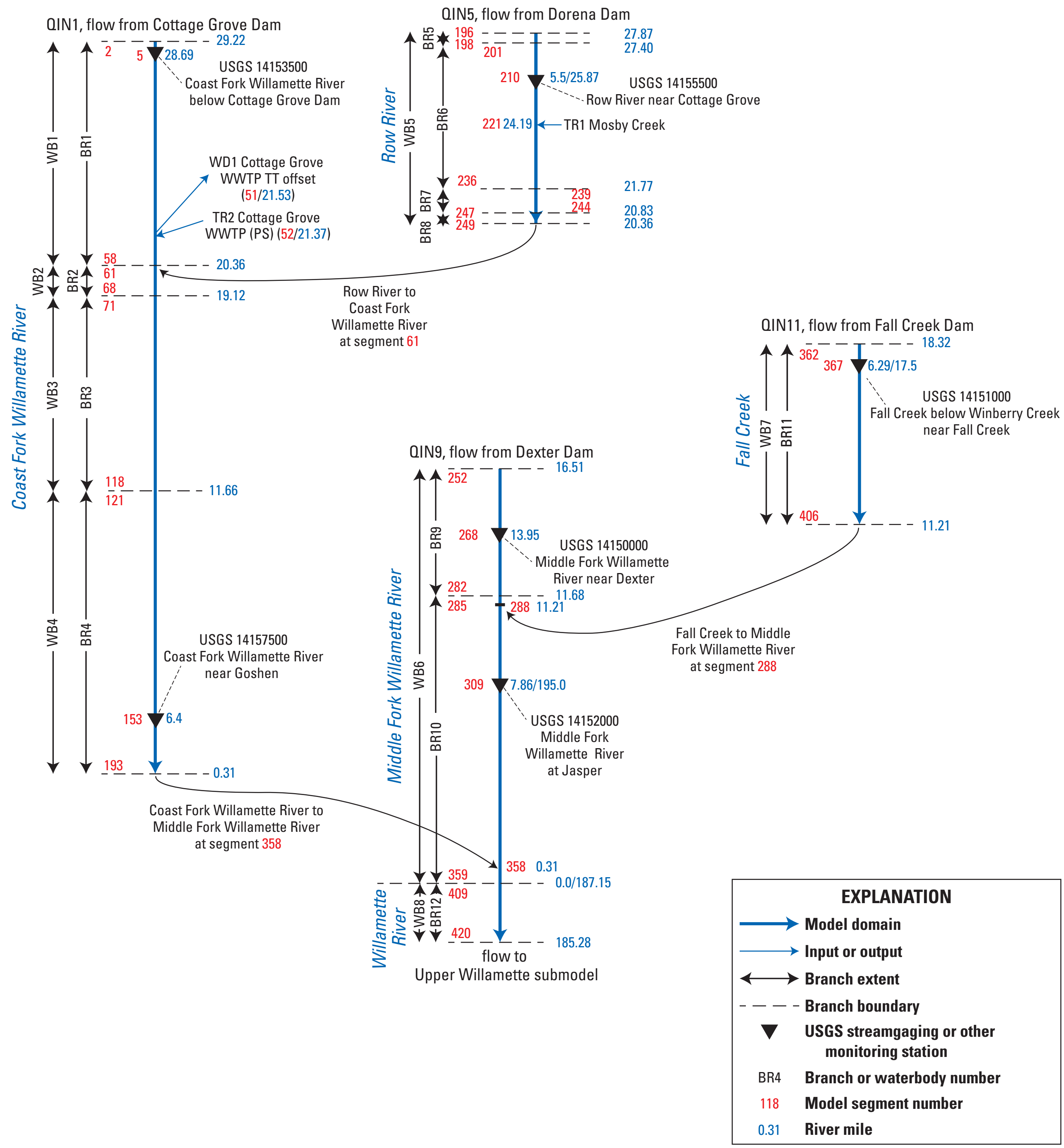


Figure 3. Diagram of the Coast Fork and Middle Fork Willamette River submodel, including locations of inflows, withdrawals, branch and waterbody boundaries, and USGS streamgaging stations or monitoring sites. Abbreviations: BR, branch; PS, point source; QIN, inflow; TR, tributary; TT, travel time; USGS, U.S. Geological Survey; WB, waterbody; WD, withdrawal; WWTP, wastewater treatment plant.

Temporal Inputs

All data sources for temporal inputs to the Coast Fork and Middle Fork Willamette River submodel are listed in table 1.

Meteorology

Meteorological data for the Coast Fork and Middle Fork Willamette River submodel were sourced from the High Point and Trout Creek Remote Automated Weather Station (RAWS; Western Regional Climate Center, 2020), Eugene Airport (Mahlon Sweet Field), the H.J. Andrews Research Forest PRIMET station (H.J. Andrews Experimental Forest Long-Term Ecological Research Network, 2020), and the University of Oregon Solar Radiation Monitoring Laboratory (SRML; University of Oregon, 2020).

In waterbodies 1 through 5, data from the High Point RAWS were used as model input for air temperature, dew-point temperature, wind speed, and wind direction. Cloud cover was as reported at Eugene Airport (Mahlon Sweet Field) (converted to CE-QUAL-W2 units as described in section “Methods and Data: Updating of Model Parameters and Inputs: Boundary Conditions”). Solar radiation was as reported by the University of Oregon SRML at Eugene. Waterbodies 6 and 7 utilized air temperature, dew-point temperature, wind speed, and wind direction recorded by the Trout Creek RAWS site. Cloud cover was as reported at Eugene Airport (Mahlon Sweet Field). Solar radiation was as reported by the H.J. Andrews PRIMET station. All meteorological data for waterbody 8 were from the Eugene Airport (Mahlon Sweet Field). All meteorological data were averaged to an hourly frequency and, where necessary, interpolated to the top of the hour.

Flow

Measured streamflow for input to branches 1, 5, 9, and 11 was available from USGS streamgaging stations 14153500 (Coast Fork Willamette River below Cottage Grove Dam; branch 1), 14155500 (Row River near Cottage Grove; branch 5), 14150000 (Middle Fork Willamette River near Dexter; branch 9), and 14151000 (Fall Creek below Winberry Creek; branch 11).

The only stream tributary included in the model is Mosby Creek, which enters the Row River (branch 6) at segment 221. No data for 2011, 2015, or 2016 were available for Mosby Creek, but Mosby Creek was gaged from 1946 to 1981 (USGS station 14156500). By comparing data from the Mosby Creek gage with data from the Row River upstream of Dorena Lake (USGS station 14154500) for the overlapping period of record (September 1, 1946 to October 13, 1981), the following regression was developed:

$$Q_{Mosby} = 10^{-0.46140*\log_{10}(Q_{14154500})} \tag{2}$$

where

Q_{Mosby} is estimated streamflow in Mosby Creek, based on a regression with USGS station 14156500, Mosby Creek at Mouth near Cottage Grove in cubic meters per second; and

$Q_{14154500}$ is measured streamflow at USGS station 14154500, in cubic meters per second.

This approach uses data from a different streamgaging station to estimate flow in Mosby Creek compared to that used for the original model, which relied on the Row River streamgaging station below Dorena Dam (USGS station 14155500). Because USGS station 14154500 (Row River above Pitcher Creek, near Dorena) is upstream of Dorena Dam, it provides a better estimate of flow in unregulated Mosby Creek than USGS station 14155500, which reflects flow modification by Dorena Dam. During 2015, modeled flow in the Coast Fork Willamette River at USGS station 14157500 (Coast Fork Willamette River near Goshen), the closest downstream streamgaging station, showed a flow peak not reflected in the measured data. This peak was traced to the estimated flow from Mosby Creek. By setting days 142 – 149 to a constant streamflow as estimated on day 141, a better fit with the streamgaging station at Goshen was achieved. It is hypothesized that a localized storm may have influenced flow in the Row River upstream of Dorena Lake, which was captured by USGS station 14154500, but that the storm did not influence flow in the Mosby Creek watershed or downstream of Dorena Lake.

Monthly discharge data for the City of Cottage Grove wastewater treatment plant (WWTP; tributary 2 in the model) were downloaded from the ECHO database for 2011, 2015, and 2016. The only withdrawal included in the model was a travel-time offset for discharges from the Cottage Grove WWTP.

Water Temperature

Data for the water temperature of all branch inflows to the models were available from USGS, including the Coast Fork Willamette River below Cottage Grove Dam (USGS station 14153500; branch 1), Row River near Cottage Grove (USGS station 14155500; branch 5), Middle Fork Willamette River at Dexter (USGS station 14150000; branch 9), and Fall Creek below Winberry Creek (USGS station 14151000; branch 11).

For the original Coast Fork and Middle Fork Willamette River submodel, temperature data for Mosby Creek were available from LASAR site 26746, with missing data filled using LASAR site 28003 from the Middle Fork Willamette River upstream of Lookout Point Lake. ODEQ was unable to provide data from LASAR sites 26746 or 28003 (D. Brown, Oregon Department of Environmental Quality, written commun., 2019), which precluded the development of a regression-based estimate or the checking of a proxy record for correlation. On the basis of similarity in drainage area and aspect, data from the Little River at Peel (USGS station 14318000) was used as a proxy record. Temperature data for the City of Cottage Grove WWTP were available on a monthly basis for 2011, 2015, and 2016, as reported in the ECHO database (U.S. Environmental Protection Agency, 2020).

The temperature of distributed tributaries was assigned using nearby monitoring station data, thus making the assumption that most of the water missing from the water budget was from small and ungaged surface-water inputs rather than from groundwater. For branches 2 and 3, temperatures from USGS station 14155500 (Row River near Cottage Grove) were assigned. For branches 9 and 10, water temperatures from USGS station 14150000 (Middle Fork Willamette River near Dexter) were assigned. For branch 12, temperatures from USGS station 14152000 (Middle Fork Willamette River at Jasper) were assigned. Distributed tributaries were not used with branches 1, 4–8, or 11.

Model Fit

Water Balance

Six USGS streamgaging stations with continuous streamflow data for 2011, 2015, and 2016 were available within the Coast Fork and Middle Fork Willamette River submodel domain. Of these streamgaging stations, four were located near the upstream branch boundaries of the four branches requiring streamflow input and were used to provide boundary input information (USGS 14155500, Row River near Cottage Grove; USGS 14151000, Fall Creek below Winberry Creek; USGS 14150000, Middle Fork Willamette near Dexter; and USGS 14153500, Coast Fork Willamette River below Cottage Grove Dam). Data from the other two streamgaging stations were used to check and calibrate model flows farther downstream within the model domain. In addition, data from a seventh streamgaging station located downstream of the model domain were used to calibrate flows in the lower reaches and to join the Coast Fork and Middle Fork Willamette River model to the Upper Willamette River submodel.

As originally constructed, the water budget in the Coast Fork and Middle Fork Willamette River submodel was balanced by calculating the difference in measured streamflows at available streamgaging stations and incorporating those flow differences into the model using five artificial tributaries in branches representing the Coast Fork and Middle Fork Willamette Rivers, an artificial tributary in the branch representing Fall Creek, and a distributed tributary in the branch representing the Willamette River downstream of the confluence of the Coast Fork and Middle Fork Willamette Rivers. The model updates documented in this report took a different approach, replacing artificial tributaries with distributed tributaries to better represent the spatial distribution of ungaged inflows to the model.

To achieve the best fit in both streamflow and water temperature at locations with available calibration data, different combinations of distributed tributaries were utilized to distribute flow across multiple upstream branches. The combination that yielded the best fit was to divide the calculated difference in streamflow at USGS station 14157500 (Coast Fork Willamette River near Goshen, model segment 153) among distributed tributaries assigned to branches 2 and 3, and the difference in streamflow at USGS station 14152000 (Middle Fork Willamette River near Jasper, model segment 309) among branches 9 and 10, and lastly to apply the difference in streamflow at the USACE streamgaging station EUGO3 near Springfield (downstream of model segment 420) to branch 12 (fig. 3; table 2).

The USACE EUGO3 streamgaging station is downstream of the Coast Fork and Middle Fork Willamette River submodel domain in the Upper Willamette River submodel. Because no streamgaging station was available at the downstream boundary of the Coast Fork and Middle Fork Willamette River submodel, the water balances for branch 1 of the Upper Willamette River submodel and branch 12 of the Coast Fork and Middle Fork Willamette River submodel had to be calculated together and then a decision made on how to best apportion the distributed flow between branch 12 of the Coast Fork and Middle Fork Willamette River submodel and branch 1 of the Upper Willamette River submodel. In all model years, the water balance for these two branches showed that streamflow in the model was overestimated relative to measured data, indicating that distributed tributary flow in the uppermost Willamette River should be negative. The City of Springfield maintains a well field adjacent to the Middle Fork Willamette River near RM 189, which may account for the loss of streamflow in that reach. For this reason, all negative computed flows for distributed tributaries in this reach were applied to branch 12 of the Coast Fork and Middle Fork Willamette River submodel and no distributed flows were applied to branch 1 of the Upper Willamette River submodel. With this adjustment and the distributed tributary flows applied to other branches, modeled and measured streamflows in the Coast Fork and Middle Fork Willamette River submodel showed good agreement (fig. 4). In 2016, missing data from the EUGO3 streamgaging station limited this check and comparison in portions of April and August.

Table 2. Location of streamflow data and distributed tributary inputs used to balance the water budgets of various CE-QUAL-W2 submodels.

[Submodel branches not listed were assigned no distributed flow. River miles are for the river listed in the data source. **Abbreviation**: QDT, distributed tributary flow]

Submodel	Measured data source	Approximate river mile	Model segment	QDT branch
Coast Fork and Middle Fork Willamette River	USGS 14157500, Coast Fork Willamette River near Goshen	6.4	153	2,3
	USGS 14152000, Middle Fork Willamette River near Jasper	9.72	309	9,10
	USACE EUGO3, Willamette River at Eugene	[1]182.5	420	12
McKenzie River	USGS 14162500, McKenzie River near Vida	44.8	106	1
	USGS 14163150, McKenzie River below Leaburg	34.5	174	2
	USGS 14163900, McKenzie River below Walterville	24.8	240	4
	USGS 14165500, McKenzie River near Coburg	4.3	372	5
South Santiam River	USGS 14187500, South Santiam River at Waterloo	21.99	134	1–4
	USGS 444113123001900, South Santiam River at RM 0.1 near Jefferson	0.1	315	5–7
North Santiam and Santiam River	USGS 14183000, North Santiam River at Mehama	38.7	110	1,2
	USGS 14184100, North Santiam River at Greens Bridge	14.6	242	3,4,5
	USGS 14189000, Santiam River at Jefferson	9.7	270	6
Upper Willamette River	USACE EUGO3, Willamette River at Eugene	182.5	19	2
	USGS 14166000, Willamette River at Harrisburg	161.0	165	2–4
	USGS 14174000, Willamette River at Albany	119.3	441	5–9
	USGS 14191000, Willamette River at Salem minus Mill Creek (City of Salem)	[2]84.2	666	10–13
Middle Willamette River	USGS 14191000, Willamette River at Newberg	50.0	248	1,2,3
	Estimated from watershed area estimation based on USGS 14202000, see Annear and others (2004)	26.6	396	5

[1]RM 182.5 is downstream of the Coast Fork and Middle Fork Willamette River submodel domain but used to calibrate the downstream-most branch of that submodel.

[2]RM 84.2 is at segment 10 of the Middle Willamette River submodel but used to calibrate branches 12–13 of the Upper Willamette River submodel.

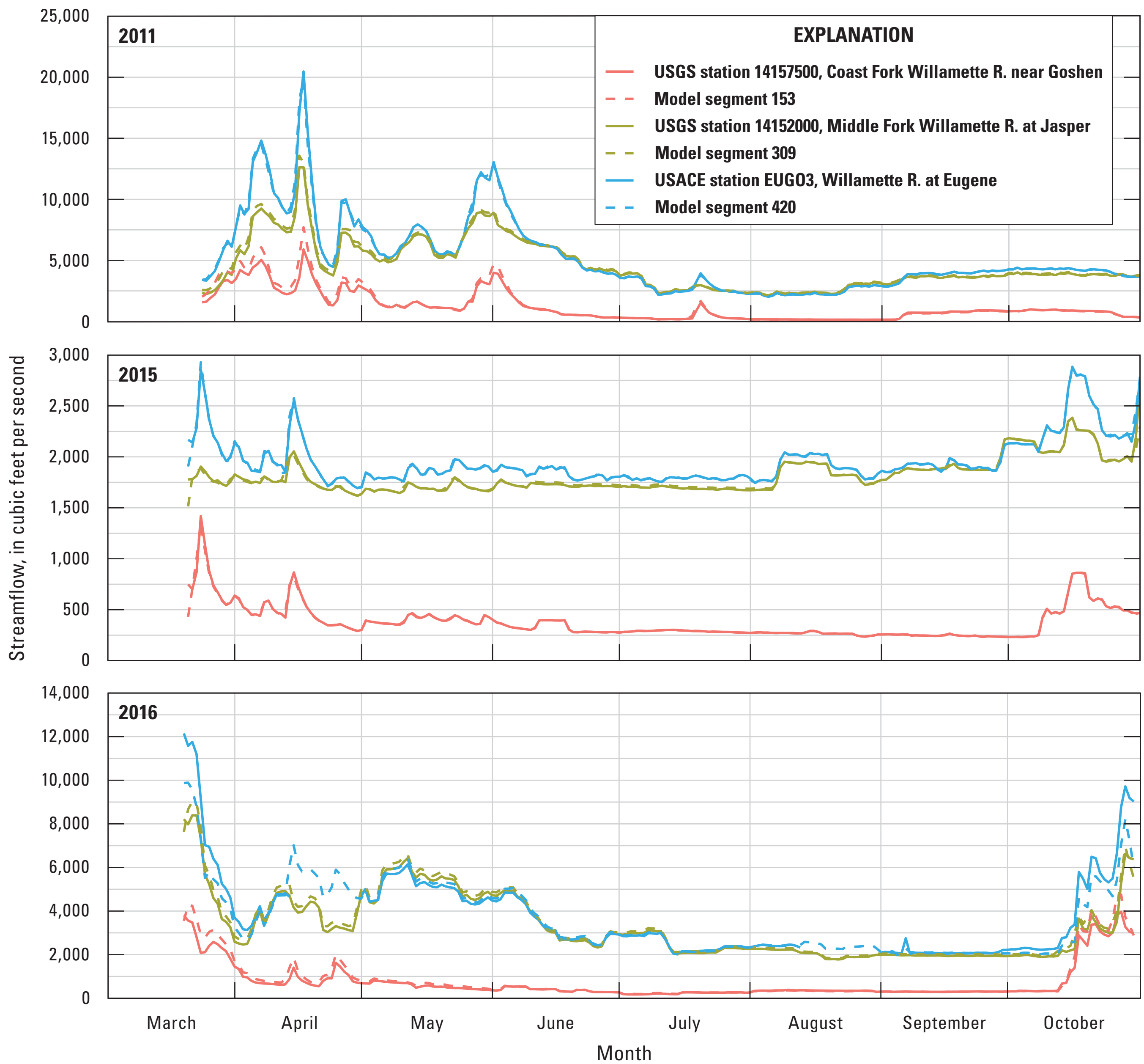


Figure 4. Daily modeled streamflow in 2011, 2015, and 2016 from the Coast Fork and Middle Fork Willamette River submodel at segments 153, 309, and 420 and measured streamflow at U.S. Geological Survey streamgaging stations 14157500 (Coast Fork Willamette River near Goshen) and 14152000 (Middle Fork Willamette River at Jasper), and U.S. Army Corps of Engineers streamgaging station EUGO3, northwestern Oregon. Where not visible, dashed lines are plotted directly over solid lines. R. river; USACE, U.S. Army Corps of Engineers; USGS, U.S. Geological Survey.

Water Temperature

Only one continuous water temperature monitoring site was available for 2011, 2015, or 2016 within the Coast Fork and Middle Fork Willamette River submodel domain: USGS station 14152000, Middle Fork Willamette River at Jasper (segment 309). Comparisons of measurements and model simulation results showed good agreement in all years at this location (fig. 5) with a slightly cool bias for some periods in all years. The subdaily mean absolute error (MAE), a measure of model fit, ranged from 0.37 °C in 2011 and 2016 to 0.48 °C in 2015 (table 3). Overall, the model appears to capture the daily range in water temperature at Jasper well, with the MAE for the daily minimum and daily maximum both less than 0.7 °C.

No temperature time series from the Willamette River within the domain of the Coast Fork and Middle Fork Willamette River submodel (branch 12) was available; however, a temperature sensor is maintained in the Willamette River at RM 178.8 at Owosso Bridge in Eugene (USGS station 14158100). Although this station is more than 6 mi downstream of the Coast Fork and Middle Fork Willamette River submodel, a visual comparison of data from this station with model simulation results from the most-downstream segment of the Coast Fork and Middle Fork Willamette River submodel is useful to assess general patterns and provide a secondary check on the model output. Applying a general summertime 0.3 °C warming adjustment over the distance from the downstream model location to station 14158100, simulated water temperatures align fairly well with measured temperatures at USGS station 14158100 (fig. 6), but the adjusted results indicate that the simulated daily minimum temperature may be biased low. The 0.3 °C warming produced the best fit and accords with downstream warming rates estimated by Rounds (2010). Diurnal variability also appears to be over-estimated by the model, as shown by the good agreement with daily maximum temperatures but underestimated daily minima; regardless, the model appears to reproduce quite well the general temperature patterns and responses to weather patterns and streamflow changes.

McKenzie River Submodel

Reach Description

The McKenzie River is a major tributary to the Willamette River that drains about 1,330 mi^2 of the foothills and upper elevations of the Cascade Range in the southeastern Willamette River Basin (Branscomb and others, 2002; U.S. Geological Survey, 2020c). Elevations in the McKenzie River Basin range from approximately 10,300 ft at the summit of South Sister to about 375 ft at the confluence of the McKenzie and Willamette Rivers at RM 175.52, near Eugene. The basin receives an average of about 76 inches of precipitation per year, and ranges from about 40 inches in the Willamette Valley to 125 inches near the crest of the Cascade Range (U.S. Geological Survey, 2020c; Risley and others, 2010a). The upper part of the basin drains the High Cascades, a permeable geologic province that supports large, year-round spring complexes that supply a steady annual flow to the McKenzie River. The middle and lower parts of the basin drain the Western Cascades, a less permeable and steeper geologic province where streamflow is more responsive to storm events (Risley and others, 2010a).

Streamflows in the McKenzie River Basin are influenced by two USACE dams and a hydropower complex owned by the Eugene Water and Electric Board (EWEB) that includes a series of regulating and diversion dams and two canals. The USACE dams are Cougar Dam on the South Fork McKenzie River and Blue River Dam on Blue River. The EWEB hydropower complex includes several regulating and storage reservoirs on the Smith River in the upper McKenzie River Basin (Risely and others, 2010a). Downstream of the South Fork McKenzie River confluence with the McKenzie River, the EWEB Leaburg and Walterville Canals divert water from the McKenzie River to produce hydropower, then return that water to the river farther downstream.

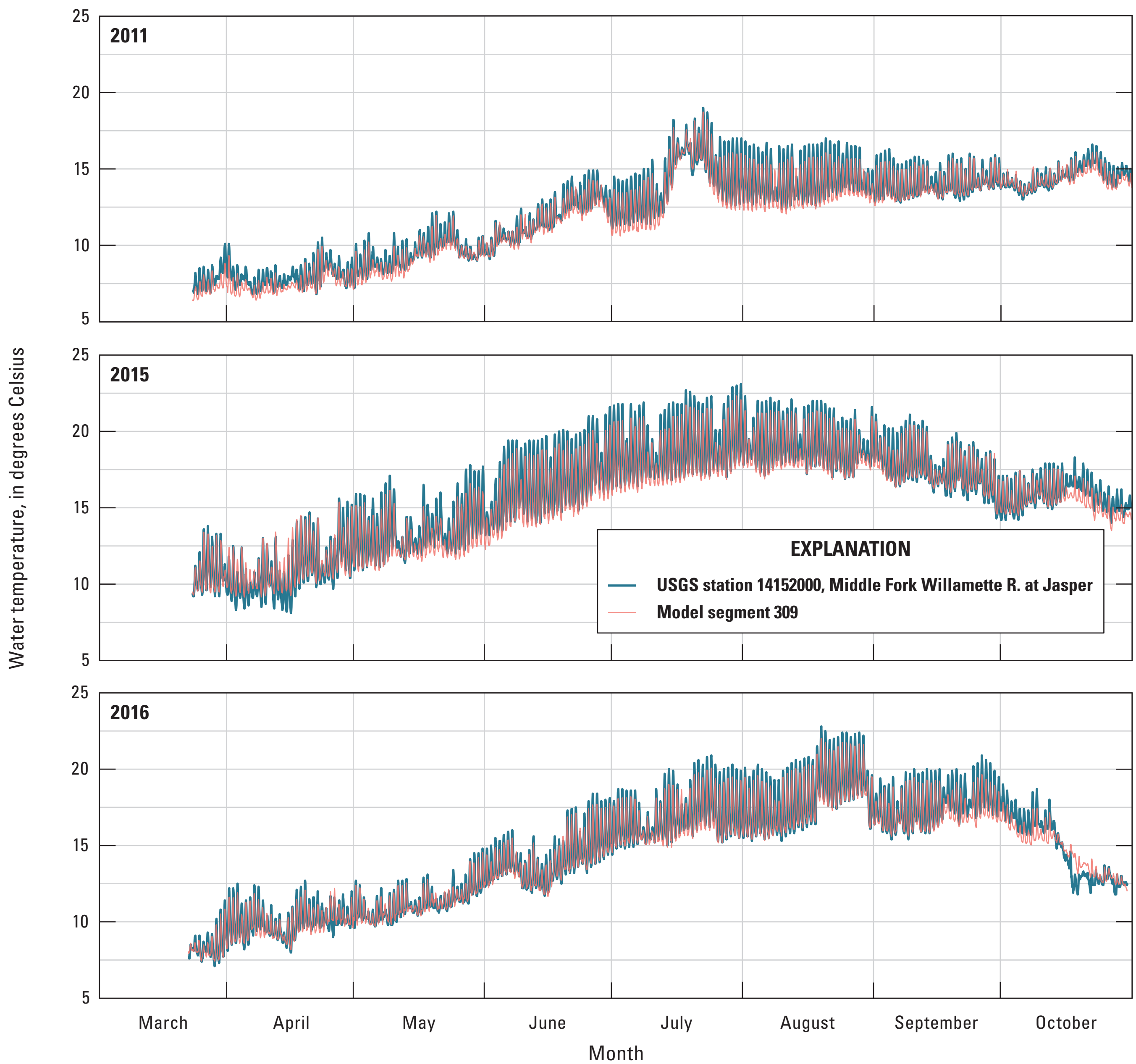


Figure 5. Subdaily modeled water temperature in 2011, 2015, and 2016 from the Coast Fork and Middle Fork Willamette River submodel at segment 309 and measured water temperature at U.S. Geological Survey station 14152000 (Middle Fork Willamette River at Jasper), northwestern Oregon. R., river; USGS, U.S. Geological Survey.

Table 3. Goodness-of-fit statistics for subdaily, daily maximum, and daily minimum stream temperature values, in degrees Celsius.

[Three spin-up days at the start of the model period were excluded from the analysis. River miles are for the river listed in the data source. **Abbreviations**: max, maximum; ME, mean error; MAE, mean absolute error; min, minimum; NA, not available; RMSE, root mean squared error]

Submodel	Approximate river mile	Model segment	Measured data source	Metric	2011			2015			2016		
					ME (degrees Celsius)	MAE (degrees Celsius)	RMSE (degrees Celsius)	ME (degrees Celsius)	MAE (degrees Celsius)	RMSE (degrees Celsius)	ME (degrees Celsius)	MAE (degrees Celsius)	RMSE (degrees Celsius)
Coast Fork and Middle Fork	9.72	309	USGS 14152000, Middle Fork Willamette River at Jasper	Subdaily	-0.32	0.37	0.46	-0.32	0.48	0.58	-0.19	0.37	0.48
				Daily max	-0.48	0.53	0.60	-0.58	0.66	0.76	-0.46	0.55	0.64
				Daily min	-0.27	0.30	0.36	-0.15	0.36	0.43	-0.04	0.25	0.37
McKenzie	44.45	106	USGS 14162500, McKenzie River near Vida	Subdaily	0.29	0.45	0.56	-0.21	0.53	0.63	0.09	0.56	0.65
				Daily max	0.26	0.49	0.59	-0.32	0.50	0.56	-0.04	0.52	0.60
				Daily min	0.35	0.38	0.49	0.12	0.38	0.47	0.35	0.47	0.59
	11.9	323	USGS 14164900, McKenzie River above Hayden Bridge	Subdaily	0.60	0.85	1.05	-0.26	0.62	0.79	0.04	0.63	0.82
				Daily max	0.98	1.13	1.37	0.06	0.50	0.63	0.30	0.70	0.90
				Daily min	0.19	0.50	0.61	-0.41	0.65	0.84	-0.09	0.48	0.62
South Santiam	0.1	315	USGS 444113123001900, South Santiam River at RM 0.1	Subdaily	-0.80	1.21	1.50	-0.56	0.97	1.25	-0.43	0.77	0.96
				Daily max	-0.94	1.18	1.46	-0.86	1.09	1.38	-0.41	0.81	1.00
				Daily min	-0.61	1.00	1.16	-0.54	0.73	0.93	-0.63	0.77	0.92
North Santiam and Santiam	37.9	115	USGS 14183010, North Santiam River near Mehama	Subdaily	-0.21	0.41	0.53	-0.08	0.56	0.70	NA	NA	NA
				Daily max	0.13	0.30	0.39	0.66	0.74	0.91	NA	NA	NA
				Daily min	-0.40	0.41	0.50	-0.51	0.51	0.60	NA	NA	NA
	31.3	150	444728122450000, North Santiam River at Geren Island	Subdaily	-0.34	0.53	0.66	-0.20	0.77	0.92	-0.09	0.83	1.05
				Daily max	0.19	0.44	0.57	0.89	0.95	1.11	0.30	0.64	0.81
				Daily min	-0.68	0.68	0.78	-1.46	1.46	1.64	-0.58	0.75	0.95
	14.6	242	USGS 14184100, North Santiam River at Greens Bridge	Subdaily	-0.74	0.88	1.07	-0.65	0.94	1.15	-0.54	0.81	1.02
				Daily max	-0.76	0.82	0.95	-1.07	1.12	1.25	-0.69	0.78	0.95
				Daily min	-0.71	0.73	0.82	-0.28	0.62	0.74	-0.35	0.59	0.68
	6.1	289	USGS 14189050, Santiam River near Jefferson	Subdaily	-0.32	0.51	0.63	-0.17	0.62	0.80	-0.15	0.45	0.59
				Daily max	-0.29	0.46	0.57	0.41	0.86	1.06	0.09	0.46	0.59
				Daily min	-0.27	0.44	0.55	-0.35	0.48	0.63	-0.20	0.39	0.52

Table 3. Goodness-of-fit statistics for subdaily, daily maximum, and daily minimum stream temperature values, in degrees Celsius. —Continued

[Three spin-up days at the start of the model period were excluded from the analysis. River miles are for the river listed in the data source. **Abbreviations**: max, maximum; ME, mean error; MAE, mean absolute error; min, minimum; NA, not available; RMSE, root mean squared error]

Submodel	Approximate river mile	Model segment	Measured data source	Metric	2011 ME (degrees Celsius)	2011 MAE (degrees Celsius)	2011 RMSE (degrees Celsius)	2015 ME (degrees Celsius)	2015 MAE (degrees Celsius)	2015 RMSE (degrees Celsius)	2016 ME (degrees Celsius)	2016 MAE (degrees Celsius)	2016 RMSE (degrees Celsius)
Upper Willamette	178.6	45	USGS 14158100, Willamette River at Owosso Bridge	Subdaily	-0.62	0.67	0.78	-0.83	1.01	1.22	-0.70	0.80	0.92
				Daily max	-0.17	0.38	0.46	0.20	0.64	0.75	-0.03	0.50	0.59
				Daily min	-0.87	0.87	0.97	-1.70	1.70	1.83	-1.10	1.11	1.19
	161.0	165	USGS 14166000, Willamette River at Harrisburg	Subdaily	-0.26	0.54	0.64	-0.44	0.74	0.88	-0.44	0.67	0.88
				Daily max	-0.04	0.46	0.57	-0.48	0.60	0.72	-0.32	0.50	0.63
				Daily min	-0.37	0.46	0.56	-0.39	0.51	0.65	-0.58	0.63	0.79
	119.3	441	USGS 14174000, Willamette River at Albany	Subdaily	-0.24	0.53	0.67	0.13	0.71	0.85	-0.01	0.66	0.86
				Daily max	0.07	0.52	0.64	0.44	0.73	0.87	0.45	0.75	0.95
				Daily min	-0.38	0.47	0.56	-0.03	0.64	0.78	-0.42	0.62	0.86
Middle Willamette	82.2	24	USGS 14192015, Willamette River at Keizer	Subdaily	-0.40	0.52	0.64	-0.20	0.62	0.76	-0.09	0.48	0.59
				Daily max	-0.48	0.54	0.66	-0.40	0.52	0.64	-0.02	0.44	0.53
				Daily min	-0.29	0.46	0.57	-0.12	0.58	0.73	-0.15	0.46	0.56
	50.0	248	USGS 14197900, Willamette River at Newberg	Subdaily	-0.32	0.49	0.63	-0.42	0.68	0.84	-0.35	0.58	0.72
				Daily max	-0.25	0.42	0.54	0.02	0.60	0.76	-0.13	0.49	0.62
				Daily min	-0.52	0.61	0.75	-0.80	0.86	1.00	-0.62	0.71	0.85

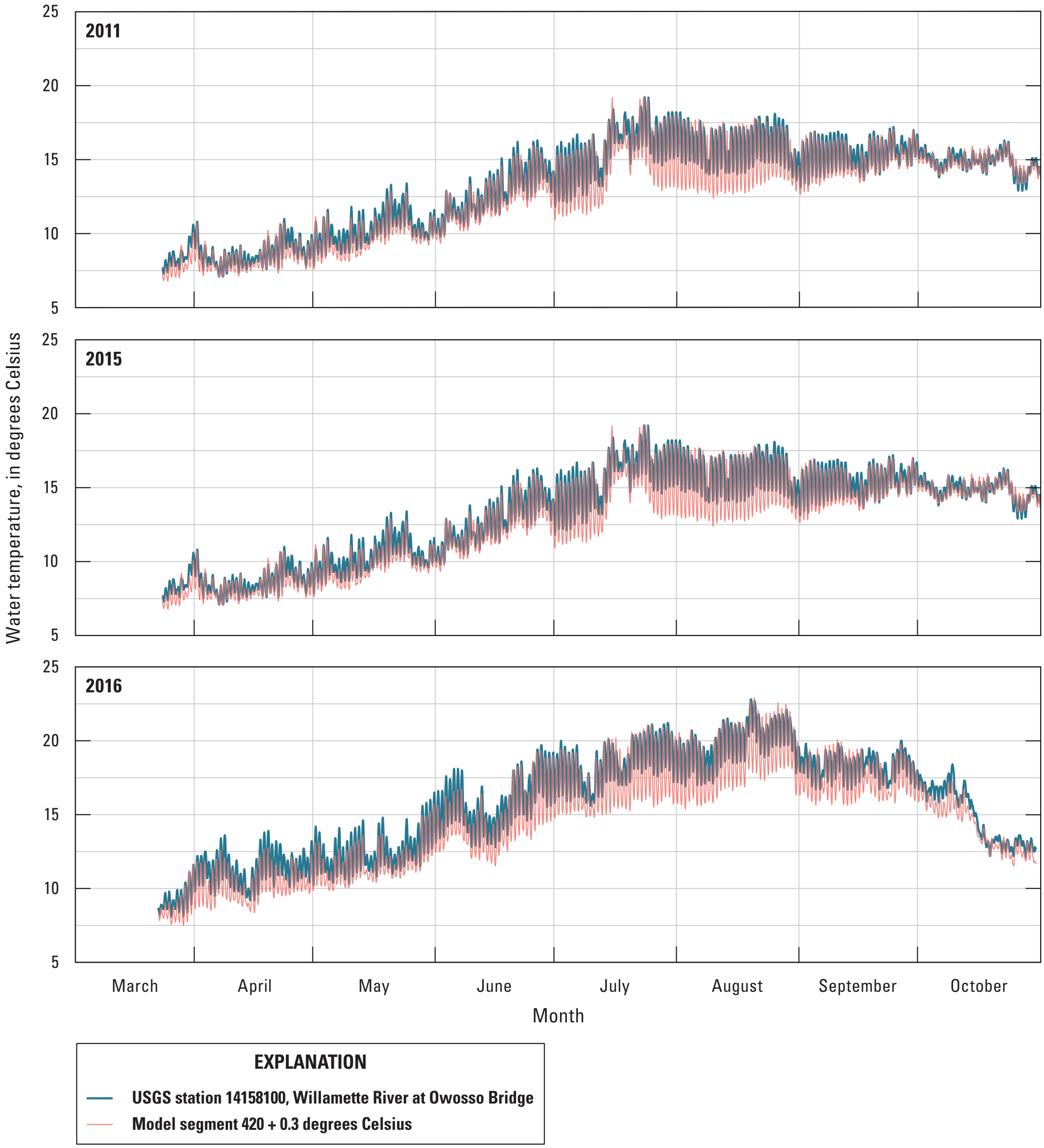


Figure 6. Subdaily modeled water temperature in 2011, 2015, and 2016 from the Coast Fork and Middle Fork Willamette River submodel at segment 420, adjusted +0.3 °C, and measured water temperature at U.S. Geological Survey (USGS) station 14158100 (Willamette River at Owosso Bridge), northwestern Oregon.

Model Domain

The McKenzie River submodel includes the South Fork McKenzie River downstream of Cougar Dam, the McKenzie River from its confluence with the South Fork McKenzie River to its confluence with the Willamette River, and the Leaburg and Walterville Canals. The submodel comprises seven waterbodies and seven branches (fig. 7). Water flows from Cougar Dam into the submodel at branch 1 and out of the submodel into the Willamette River from branch 5; the Leaburg Canal is represented by branch 6 and the Walterville Canal by branch 7.

Fourteen model tributaries include nine real tributaries to the McKenzie River, one point source, three artificial tributaries that originally accounted for ungaged flow into the model domain (an artifact of the original models that are assigned no flow in 2011, 2015, or 2016), and one artificial tributary that prevents the model from drying up and failing when flow into the Walterville Canal is turned off. In the updated model, four distributed tributaries account for ungaged flows. Two withdrawals are included in the model: the first provides an artificial travel-time correction for the point source, and the second is a companion to the false Walterville Canal tributary, which introduces “fake” water into the Walterville Canal to prevent the model from failing when measured flow into the Walterville Canal is zero. The second withdrawal in the McKenzie River submodel removes the “fake” water from the end of the Walterville Canal prior to its re-entry into the McKenzie River, preventing this model fix from affecting the modeled temperatures downstream.

Bathymetric Grid and Non-Temporal Parameters

Development and calibration of the bathymetric grid was documented by Annear and others (2004) and Berger and others (2004). No changes to the bathymetric grid were made when updating the models except to convert the files to a newer format, to move the location of the Mohawk River tributary slightly upstream to a more accurate location, and to apply appropriate initial water surface elevations for 2011, 2015, and 2016.

Temporal Inputs

All data sources for temporal inputs to the McKenzie River submodel are listed in table 1.

Meteorology

Meteorological data for the McKenzie River submodel were sourced from the Trout Creek RAWS station, the Eugene Airport (Mahlon Sweet Field), the University of Oregon Solar Radiation Monitoring Lab, and the H.J. Andrews Research Forest PRIMET station, after Annear and others (2004). For waterbody 1, all meteorological data were sourced from the H.J. Andrews PRIMET station except for cloud cover, which was converted to CE-QUAL-W2 units from reported values at the Eugene Airport (Mahlon Sweet Field), as described in section “Methods and Data: Updating of Model Parameters and Inputs: Boundary Conditions.” In 2016, missing air temperature data from the H.J. Andrews PRIMET station were filled using a regression with data from the High Point, Oregon RAWS station, estimated as:

$$A\,T_{PRIMET} = 1.036474 * A\,T_{HighPoint} - 1.029527 \quad (3)$$

where

$A\,T_{PRIMET}$ is measured air temperature at the H.J. Andrews PRIMET station, in degrees Celsius; and

$A\,T_{HighPoint}$ is measured air temperature at the High Point RAWS station, in degrees Celsius.

Waterbodies 2, 3, and 6 use air temperature, dew-point temperature, wind speed, and wind direction sourced from the Trout Creek RAWS station, reported cloud cover from the Eugene Airport (Mahlon Sweet Field), and solar radiation from the H.J. Andrews PRIMET station. Waterbodies 4, 5, and 7 use air temperature, dew-point temperature, wind speed, wind direction, and cloud cover as reported at the Eugene Airport (Mahlon Sweet Field) and solar radiation from the University of Oregon SRML at Eugene. Dew-point temperature was calculated on the basis of measured relative humidity using the “weathermetrics” package in R, which follows the methodology established by NOAA (Anderson and others, 2016).

All meteorological data were averaged to an hourly frequency and, where necessary, interpolated to the top of the hour.

Flow

The McKenzie River submodel includes flow from the South Fork McKenzie River, nine real tributaries, one point source, two canals, and four distributed tributaries (fig. 7). All streamflow inputs to the model were averaged to a daily frequency.

Measured flow data for 2011, 2015, and 2016 were available for the South Fork McKenzie River, two tributaries, inflow to the two canals, and the point source. Measured inflow data for the South Fork McKenzie River were available from USGS station 14159500 (South Fork McKenzie River near Rainbow). Streamflow from Blue River was available from USGS station 14162200 (Blue River at Blue River). Streamflow in the Mohawk River was available from USGS station 14165000 (Mohawk River near Springfield). Inflow to the Leaburg and Walterville Canals was provided by EWEB (M. Zinniker, D. Donahue, and K. Morgenstern, Eugene Water and Electric Board, written commun., 2019). Discharge data from the International Paper mill in Springfield (formerly Weyerhaeuser Company) were provided by ODEQ; because data were not available for 2016, values from 2015 were applied as proxies to the 2016 model.

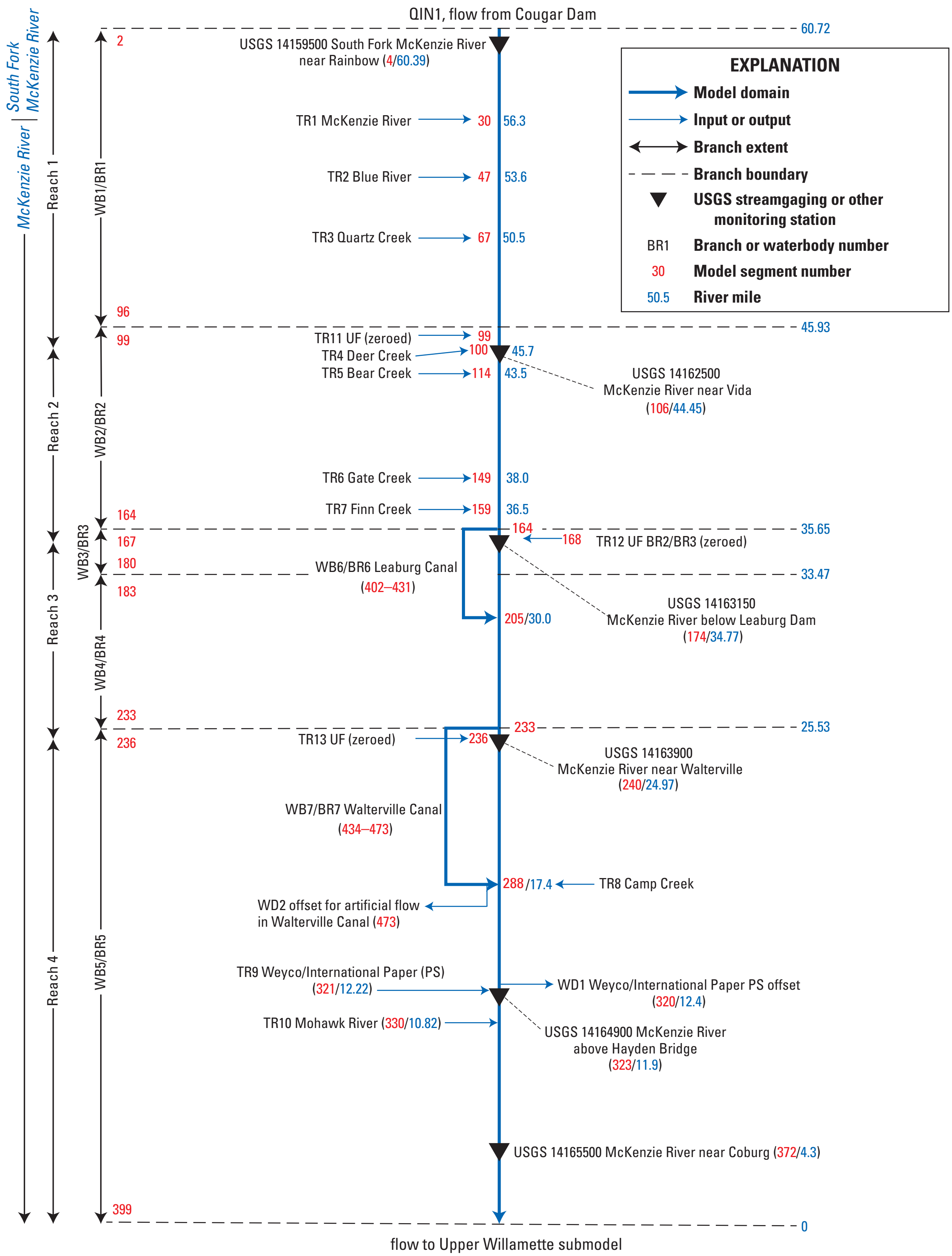


Figure 7. McKenzie River submodel, including locations of inflows, withdrawals, branch and waterbody boundaries, reaches for the computed water balance, and USGS streamgaging stations or monitoring sites. Abbreviations: BR, branch; PS, point source; QIN, inflow; TR, tributary; UF, ungaged flow; USGS, U.S. Geological Survey; WB, waterbody; WD, withdrawal.

The original setup of the McKenzie River submodel used a reach-based, weighted watershed area ratio method to assign inflow to ungaged tributaries and other ungaged flows (Annear and others, 2004; Berger and others, 2004; see also section "Methods and Data: Updating of Model Parameters and Inputs: Boundary Condition Estimation Methods"). In that original approach, USGS streamgaging stations 14159500 (South Fork McKenzie River near Rainbow), 14162500 (McKenzie River near Vida), 14163150 (McKenzie River below Leaburg Dam), and 14163900 (McKenzie River near Walterville) were used to divide the model domain into four reaches (fig. 7), from which flow was apportioned according to watershed area ratios.

Reach 1 for the water balance was bounded by USGS streamgaging station 14159500 (South Fork McKenzie River near Rainbow) at the upstream end and by USGS streamgaging station 14162500 (McKenzie River near Vida) at the downstream end. Flow into reach 1 includes the South Fork McKenzie River (upstream inflow; measured), the McKenzie River (tributary; estimated), Blue River (tributary; measured), Quartz Creek (tributary; estimated), Deer Creek (tributary; estimated), flow from several small tributaries not included as tributaries in the submodel, and any estimated groundwater inflow.

Flow data for the McKenzie River immediately upstream of its confluence with the South Fork McKenzie River were not available for 2011, 2015, or 2016. However, USGS streamgaging station 14159000 (McKenzie River at McKenzie Bridge), located on the McKenzie River approximately 10 miles upstream of the confluence with the South Fork McKenzie River, was operated from 1987 to 1994. When the submodel was originally built, inflow from the McKenzie River was estimated by using a regression between USGS streamgaging stations 14159000 and 14162500 (McKenzie River near Vida), with an R^2 value of 0.86 (Annear and others, 2004). Despite the fact that flow at the streamgaging station at Vida is influenced by outflows from both Cougar Dam on the South Fork McKenzie River and Blue River Dam on Blue River, sensitivity analyses using data from nearby streamgaging stations did not indicate that regressions with other streamgaging stations operating in 2011, 2015, and 2016 could provide a better estimate of streamflow. Inflow from the McKenzie River to the McKenzie River submodel was thus estimated following Annear and others (2004) as:

$$Q_{McKenzie} = 0.2538 * Q_{14162500} - 5.0107x\,10^{-5} * Q_{14162500}{}^{2} + 18.9024 \quad (4)$$

where

$Q_{McKenzie}$ is measured streamflow at USGS station 14159000, McKenzie River at McKenzie Bridge, in cubic meters per second; and

$Q_{14162500}$ is measured streamflow at USGS station 14162500, McKenzie River near Vida, in cubic meters per second.

Streamflow in Quartz and Deer Creeks was estimated using the weighted watershed area ratio method discussed above, after Annear and others (2004):

$$Q_{Quartz} = 0.4075 * (Q_{14162500} - Q_{14162200} - Q_{14159000(estimated)}) \quad (5)$$

$$Q_{Deer} = 0.1172 * (Q_{14162500} - Q_{14162200} - Q_{14159000(estimated)}) \quad (6)$$

where

Q_{Quartz} is estimated streamflow in Quartz Creek, in cubic meters per second;

Q_{Deer} is estimated streamflow in Deer Creek, in cubic meters per second;

$Q_{14159000}$ is estimated streamflow at USGS station 14159000, McKenzie River at McKenzie Bridge, in cubic meters per second;

$Q_{14162200}$ is measured streamflow at USGS station 14162200, Blue River at Blue River, in cubic meters per second; and

$Q_{14162500}$ is measured streamflow at USGS station 14162500, McKenzie River near Vida, in cubic meters per second.

Coefficients in equations 5 and 6 represent the watershed area ratio between Quartz and Deer Creeks, respectively, and the ungaged watershed area in reach 1. The remaining ungaged flow (including ungaged surface flow and any groundwater inflow) was estimated using the methods of Annear and others (2004):

$$Q_{DT1} = 0.4753 * (Q_{14162500} - Q_{14162200} - Q_{14159000(estimated)}) \quad (7)$$

where

Q_{DT1} is the initial estimate of ungaged flow in reach 1 of the McKenzie River submodel, in cubic meters per second.

The coefficient in equation 7 represents the fraction of ungaged flow in reach 1 not accounted for by Quartz or Deer Creeks. This result was incorporated into the model as an initial estimate of ungaged flow in the distributed tributary in branch 1.

Reach 2 for the water balance was bounded by USGS streamgaging station 14162500 (McKenzie River at Vida) at its upstream end and by USGS streamgaging station 14163150 (McKenzie River below Leaburg Dam) at its downstream end. Tributaries in reach 2 include Bear Creek (estimated), Gate Creek (estimated), Finn Creek (estimated), flow from several small ungaged tributaries not explicitly included in the model, and groundwater. Additionally, flow into the Leaburg Canal (measured) is diverted from the McKenzie River in reach

2. Following the methodology of Annear and others (2004), streamflows from Bear, Gate, and Finn Creeks were estimated using a weighted watershed area approach, as follows:

$$Q_{Bear} = 0.0894*\left(Q_{14163150} - \left(Q_{14162500} - Q_{Leaburg\ Canal}\right)\right) \quad (8)$$

$$Q_{Gate} = 0.4716*\left(Q_{14163150} - \left(Q_{14162500} - Q_{Leaburg\ Canal}\right)\right) \quad (9)$$

$$Q_{Finn} = 0.0471*\left(Q_{14163150} - \left(Q_{14162500} - Q_{Leaburg\ Canal}\right)\right) \quad (10)$$

Coefficients in equations 8, 9, and 10 represent the watershed area ratios between Bear, Gate, and Finn Creeks, respectively, and the ungaged watershed area in reach 2. The remaining ungaged flow (including ungaged surface flow and any groundwater inflow) was estimated after Annear and others (2004):

$$Q_{DT2} = 0.3920*\left(Q_{14163150} - \left(Q_{14162500} - Q_{Leaburg\ Canal}\right)\right) \quad (11)$$

where

Q_{Bear} is estimated streamflow in Bear Creek, in cubic meters per second;

$Q_{14163150}$ is measured streamflow at USGS station 14163150, McKenzie River below Leaburg Dam, in cubic meters per second;

$Q_{14162500}$ is measured streamflow at USGS station 14162500, McKenzie River at Vida, in cubic meters per second;

$Q_{Leaburg\ Canal}$ is measured streamflow diverted to Leaburg Canal, in cubic meters per second;

Q_{Gate} is estimated streamflow in Gate Creek, in cubic meters per second;

Q_{Finn} is estimated streamflow in Finn Creek, in cubic meters per second; and

Q_{DT2} is the initial estimate of ungaged flow in reach 2 of the McKenzie River submodel, in cubic meters per second.

The coefficient in equation 11 represents the fraction of ungaged flow in reach 2 not accounted for by Bear, Gate, or Finn Creeks. Q_{DT2} was used in the submodel as an initial estimate of distributed flow in branch 2, which was then refined in the model calibration process.

Reach 3 for the water balance was bounded by USGS streamgaging station 14163150 (McKenzie River below Leaburg Dam) at its upstream end and by USGS streamgaging station 14163900 (McKenzie River near Walterville) at its downstream end. Water diverted into the Leaburg Canal upstream returns to the McKenzie River in reach 3. Water is diverted to the Walterville Canal (measured) at the downstream boundary of reach 3, and no modeled tributaries flow into reach 3 (fig. 7). Ungaged flow was calculated using the same approach as in the reaches upstream, but the water balance calibration showed that the model fit was better without the addition of any computed ungaged inflows. No distributed tributary flow was applied to branch 3 of the McKenzie River submodel.

Reach 4 extends from USGS streamgaging station 14163900 (McKenzie River near Walterville) to the downstream end of the model at the confluence of the McKenzie River with the Willamette River. Inflow to reach 4 includes Camp Creek (estimated), return flows from the Walterville Canal (modeled), point-source effluent from International Paper (measured), and the Mohawk River (measured). Streamflow in Camp Creek was estimated using a watershed area comparison with the Mohawk River (Annear and others, 2004):

$$Q_{Camp} = 0.147*Q_{14165000} \quad (12)$$

where

Q_{Camp} is estimated streamflow in Camp Creek, in cubic meters per second; and

$Q_{14165000}$ is measured streamflow at USGS station 14165000, Mohawk River near Springfield, in cubic meters per second.

The coefficient in equation 12 represents the ratio between the watershed area of Camp Creek and the watershed area of the Mohawk River at USGS station 14165000.

Flow into the Walterville Canal was occasionally turned off in 2011, 2015, and 2016. To prevent the model from failing due to the “drying up” of branch 7, a false tributary was added to the upstream-most segment of branch 7, the Walterville Canal. During periods when the Walterville Canal was dry, this false tributary provided artificial flow into branch 7 so that the branch would remain active and prevent the model from failing. This artificial flow was then removed at the bottom of branch 7 using a withdrawal from the model to preclude any influence of the artificial flow on the McKenzie River downstream of the Walterville Canal return.

Two withdrawals were included in the McKenzie River submodel, both of which were artificial. The first was located immediately upstream of the International Paper point source, and removes a flow equal to that of the point source as a travel-time correction (see Rounds, 2007). The second accounts for the artificial flow added to the Walterville Canal as a fix to prevent model failure, as discussed above.

Water Temperature

Measured water temperature data for input into the McKenzie River submodel were available for the South Fork McKenzie River, Blue River, the International Paper point source in Springfield, and the Mohawk River. All other input temperatures were estimated. When originally built for conditions in 2001 and 2002, the McKenzie River submodel relied on a variety of continuous temperature monitors installed for that purpose. Data from those sources were unavailable for 2011, 2015, and 2016 but were used in some cases to build regression models to estimate the stream temperatures required by the model.

The temperature of the McKenzie River upstream of its confluence with the South Fork McKenzie River was measured at USGS station 14159110 in parts of the years 2003 through 2006. Using a regression with data from USGS station 14159200 (South Fork McKenzie River above Cougar Lake; overlapping data period January 29, 2003, to September 30, 2006), the temperature in the McKenzie River upstream of the South Fork McKenzie River was estimated for 2011, 2015, and 2016 as follows:

$$T_{McKenzie} = 0.8140546 * T_{14159200} + 1.6931141 \tag{13}$$

where

$T_{McKenzie}$ is estimated water temperature of the McKenzie River upstream of the South Fork McKenzie River, in degrees Celsius; and

$T_{14159200}$ is measured water temperature at USGS station 14159200, South Fork McKenzie River above Cougar Lake, in degrees Celsius.

Continuous temperature data from the original 2001-2002 McKenzie River submodel were available for Deer Creek, Bear Creek, and Finn Creek (D. Brown, Oregon Department of Environmental Quality, written commun., 2019). By comparing these data to temperature data from the South Fork McKenzie River above Cougar Lake (USGS station 14159200), the following estimates of temperature were used in the model update:

$$T_{Deer} = 0.9919423 * T_{14159200} + 4.2007112 \tag{14}$$

$$T_{Bear} = 0.709 * T_{14159200} + 6.073 \tag{15}$$

$$T_{Finn} = 0.7107 * T_{14159200} + 5.2052 \tag{16}$$

where

T_{Deer} is estimated water temperature of Deer Creek, based on data from LASAR site 28144, in degrees Celsius;

T_{Bear} is estimated water temperature of Bear Creek, based on data from LASAR site 28108, in degrees Celsius;

T_{Finn} is estimated water temperature of Finn Creek, based on data from LASAR site 28115, in degrees Celsius; and

$T_{14159200}$ is measured water temperature at USGS station 14159200, South Fork McKenzie River above Cougar Lake, in degrees Celsius.

Temperatures for Camp Creek, which is near the Mohawk River, were estimated as:

$$T_{Camp} = 0.8131 * T_{14165000} + 1.5416 \tag{17}$$

where

T_{Camp} is estimated water temperature of Camp Creek, based on data from USGS station 14164550, Camp Creek at Camp Creek Road Bridge near Springfield, in degrees Celsius; and

$T_{14165000}$ is measured water temperature at USGS station 14165000, Mohawk River near Springfield, in degrees Celsius.

For Quartz Creek, the estimated water temperature in Deer Creek was assigned. For Gate Creek, the estimated temperature in Bear Creek was used. This approach applies the closest available record to Quartz and Gate Creeks and was shown to produce the best model fit in testing with other proxy records.

The temperatures of the distributed tributaries computed from the water balance were assigned on the basis of temperatures from real, commonly nearby tributaries. The water temperature of ungaged flow in branch 1 was estimated using the estimated temperature of Deer Creek as a proxy. The temperature of ungaged flow in branch 2 was estimated using the estimated temperature of Bear Creek as a proxy. Ungaged flow in distributed tributaries in branches 4 and 5 were assigned the estimated temperature of Camp Creek as a proxy.

Model Fit

Water Balance

In the original model setup, flow from “distributed area” not otherwise accounted for in the reach-based weighted watershed area approach was assigned to an artificial tributary. The artificial tributaries were added to the model several segments upstream of each reach boundary and were used in place of distributed tributaries in the submodel. The original model documentation states that this approach was utilized because the branch boundaries of the model did not coincide with the reach boundaries predicated on streamgaging station locations (Annear and others, 2004). However, due to the known influence of groundwater on streamflow in the McKenzie River Basin, when the models were updated it was felt that this approach was not the method most likely to accurately simulate conditions in the McKenzie River. Instead, ungaged flow (ungaged surface flow and any groundwater) was accounted for by providing flow rates of zero to the artificial tributaries in the original submodel, adding distributed tributaries to the McKenzie River submodel, and performing an iterative water balance calibration as with the other submodels. When compared, this updated approach yielded similar or slightly better goodness-of-fit statistics at locations where measured streamflow data were available.

The water budget in the McKenzie River submodel was calibrated iteratively. Distributed tributaries were initially calculated according to the reach-based methodology of Annear and others (2004), which included “other ungaged flow” in the watershed-area-based estimation of water-balance flows, then refined by comparing modeled to measured streamflows at the gages near branch boundaries (table 2) and adjusting the distributed tributary flows of branches upstream until the modeled and measured flows showed good agreement (fig. 8). For 2015, this method of estimating the ungaged flows caused the modeled flow at Hayden Bridge to be over-estimated. Both the Hayden Bridge and Coburg streamgages are within branch 5, however, and thus influenced by a single distributed tributary, which precludes achieving a perfect fit at both locations. The decision to prioritize the fit at Coburg over the fit at Hayden Bridge was made to allow input to the Upper Willamette River submodel to be as accurate as possible. Note that the flow in the natural river channel is artificially low in those reaches where substantial flows were diverted out of the river and into the Leaburg and Walterville Canals.

Water Temperature

Continuous water temperature data were available at two locations in the McKenzie River submodel domain for the years 2011, 2015, and 2016. Comparison of modeled and measured water temperature at Vida (segment 106; fig. 7) indicates that the model may slightly overestimate diurnal variability (fig. 9), but subdaily goodness-of-fit statistics are excellent, with MAE ranging from 0.45 °C in 2011 to 0.56 °C in 2016 (table 3). Comparisons at Hayden Bridge (segment 323) are also good, ranging from 0.62 to 0.85 °C (fig. 10; table 3). Sensitivity testing indicated that the model fit at these two locations was almost identical (within several hundredths of a degree Celsius) using the artificial tributaries set up in the original model (Berger and others, 2004; Annear and others, 2004) compared to the use of distributed tributaries. Implementation of distributed tributaries was deemed to be a better representation of real conditions in the McKenzie River; therefore, that approach was used in the final models.

South Santiam River Submodel

Reach Description

The South Santiam River, a major tributary to the Santiam River, drains about 1,040 mi^2 of the Cascade Range foothills and Willamette Valley (Branscomb and others, 2002; U.S. Geological Survey, 2020c). The South Santiam River Basin ranges in elevation from 220 to 5,271 ft. Given its relatively low elevation compared to that of other sub-basins in the Cascade Range, the South Santiam River Basin receives most of its precipitation as rain. Its upper reaches are sourced entirely in the steep and relatively low permeability Western Cascades geologic province (Risley and others, 2012), causing streamflow to be more responsive to rainfall and snowmelt, and stream temperatures to be warmer than those in basins with predominantly High Cascades geology. The South Santiam River joins the North Santiam River near the town of Jefferson. Major tributaries downstream of Foster Dam include Wiley, McDowell, Hamilton, Crabtree, and Thomas Creeks. Major dams in the basin include Foster and Green Peter Dams, with the latter impounding a high-head storage reservoir, and the former acting mainly as a re-regulating dam downstream of the latter.

Model Domain

The South Santiam River submodel consists of the South Santiam River from RM 36.50 at Foster Dam to RM 0 at its confluence with the North Santiam River (fig. 11). The submodel comprises five waterbodies and seven branches. Branches 1 and 4 through 7 represent the main channel of the South Santiam River, whereas branches 2 and 3 are side channels connected to branch 1. Five tributaries, two point sources, one major withdrawal, and two travel-time offset withdrawals are included in the model.

When this model was originally developed, Bloom (2016) noted a discrepancy between river length as commonly reported and that measured by the GIS-based model grid development. This report uses the adjusted river miles consistent with the CE-QUAL-W2 model grid, after Bloom (2016). A cross-walk between reported river miles and those in the model is provided in Bloom (2016).

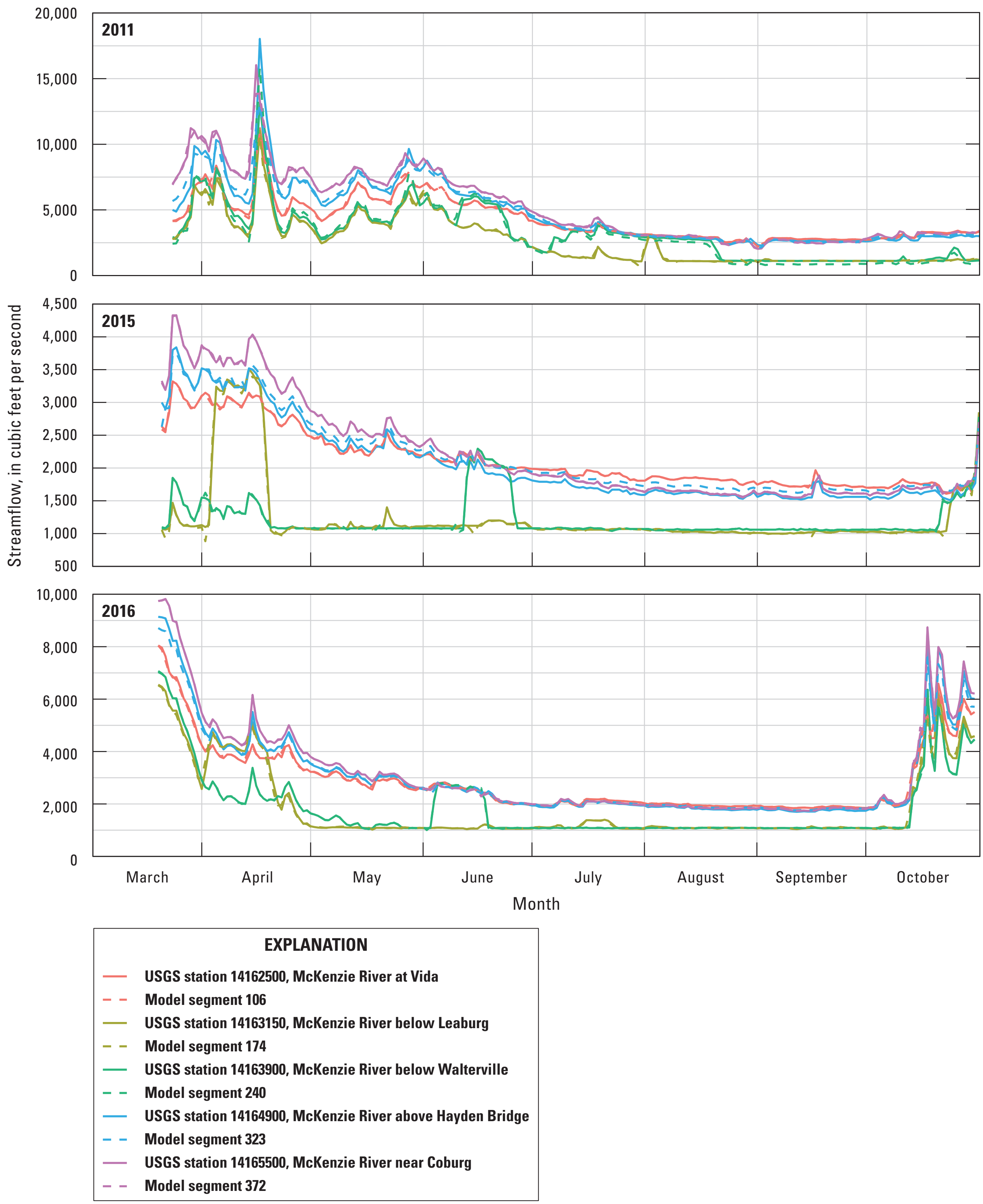


Figure 8. Graphs showing daily modeled streamflow in 2011, 2015, and 2016 from the McKenzie River submodel at segments 106, 174, 240, 323, and 372 and measured streamflow at U.S. Geological Survey (USGS) streamgaging stations, northwestern Oregon. Where not visible, dashed lines are plotted directly over solid lines.

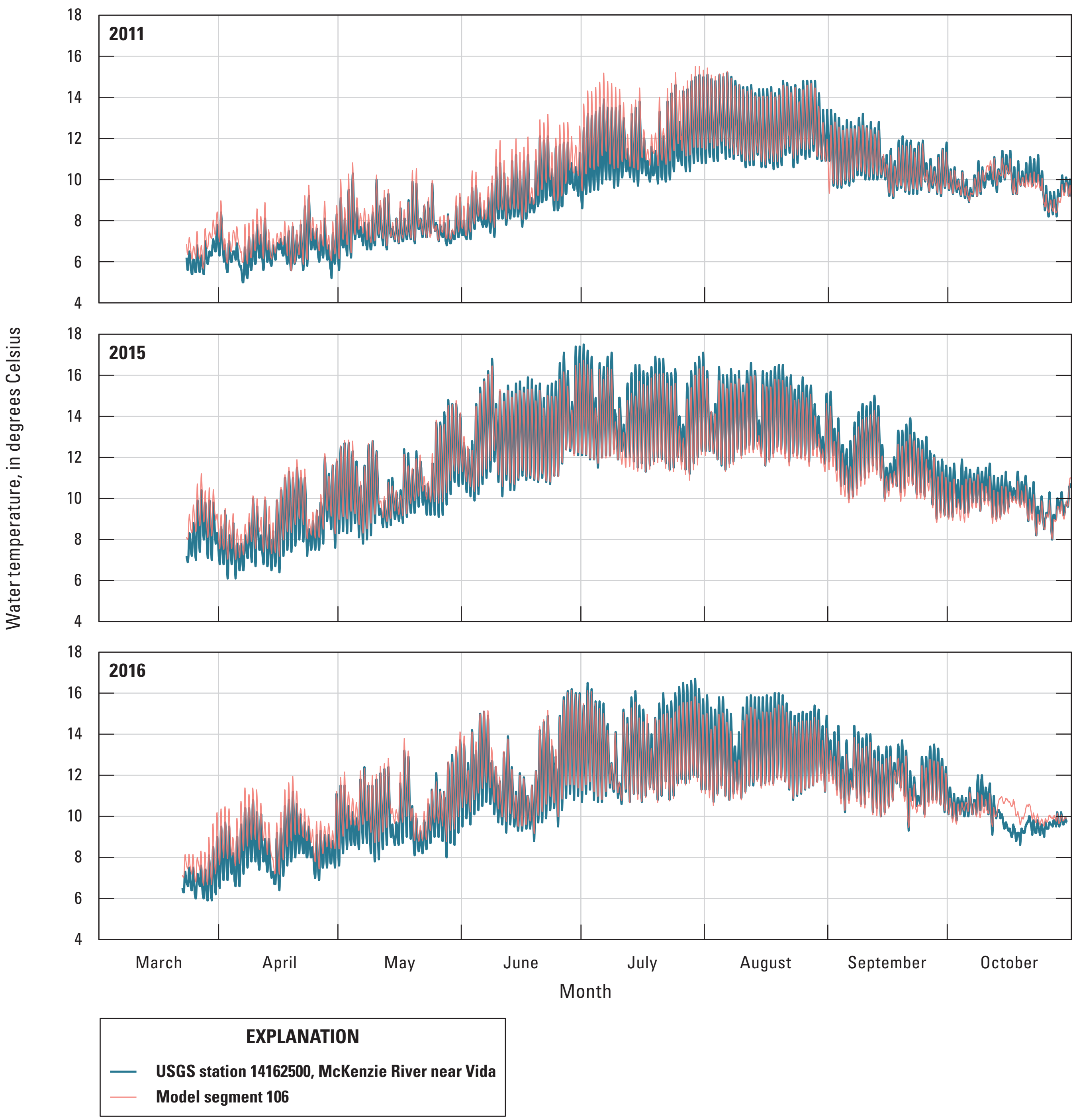


Figure 9. Subdaily modeled water temperature in 2011, 2015, and 2016 from the McKenzie River submodel at segment 106 and measured water temperature at U.S. Geological Survey (USGS) station 14162500 (McKenzie River near Vida), northwestern Oregon.

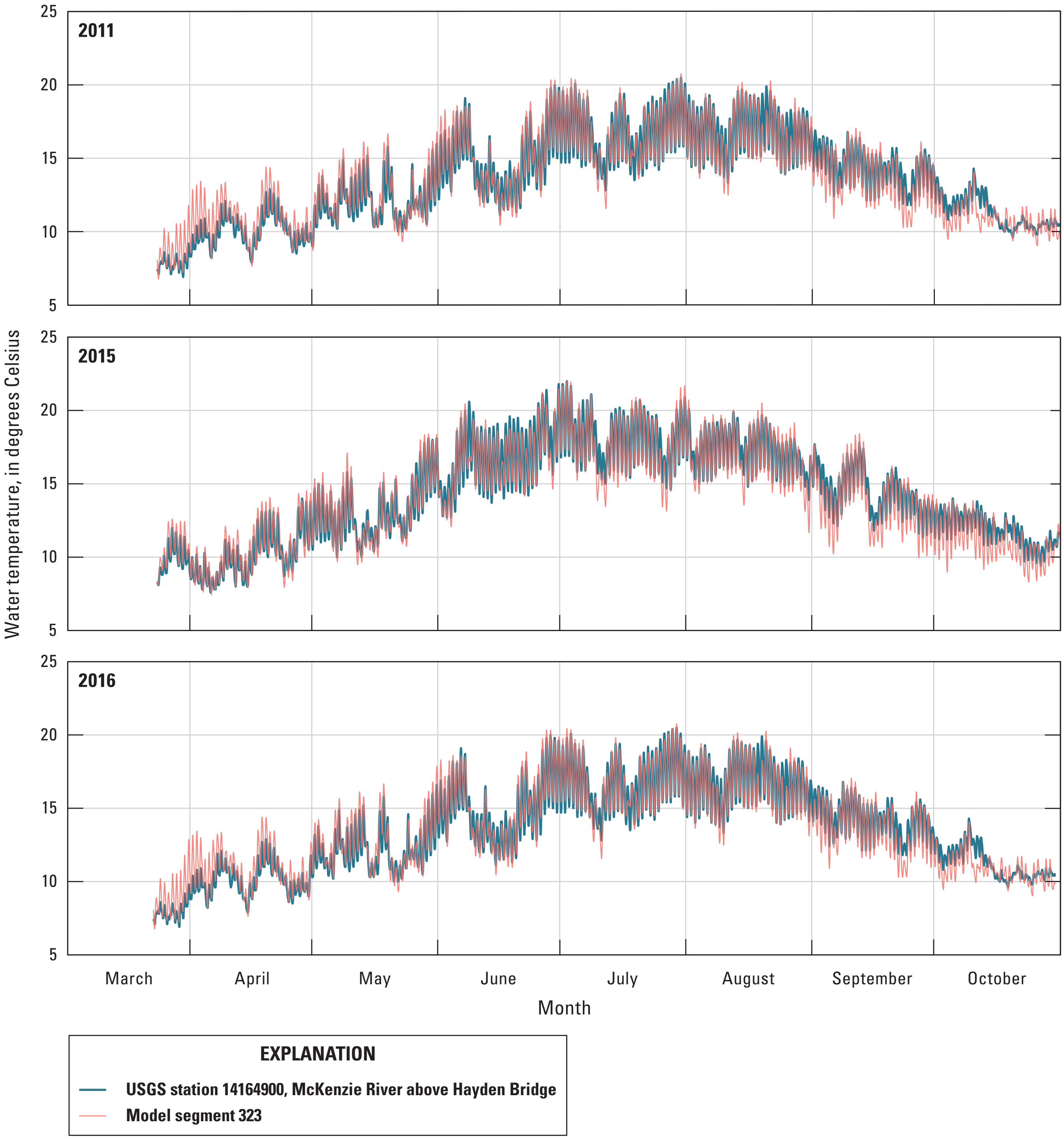


Figure 10. Subdaily modeled water temperature in 2011, 2015, and 2016 from the McKenzie River submodel at segment 323 and measured water temperature at U.S. Geological Survey (USGS) station 14164900 (McKenzie River above Hayden Bridge), northwestern Oregon.

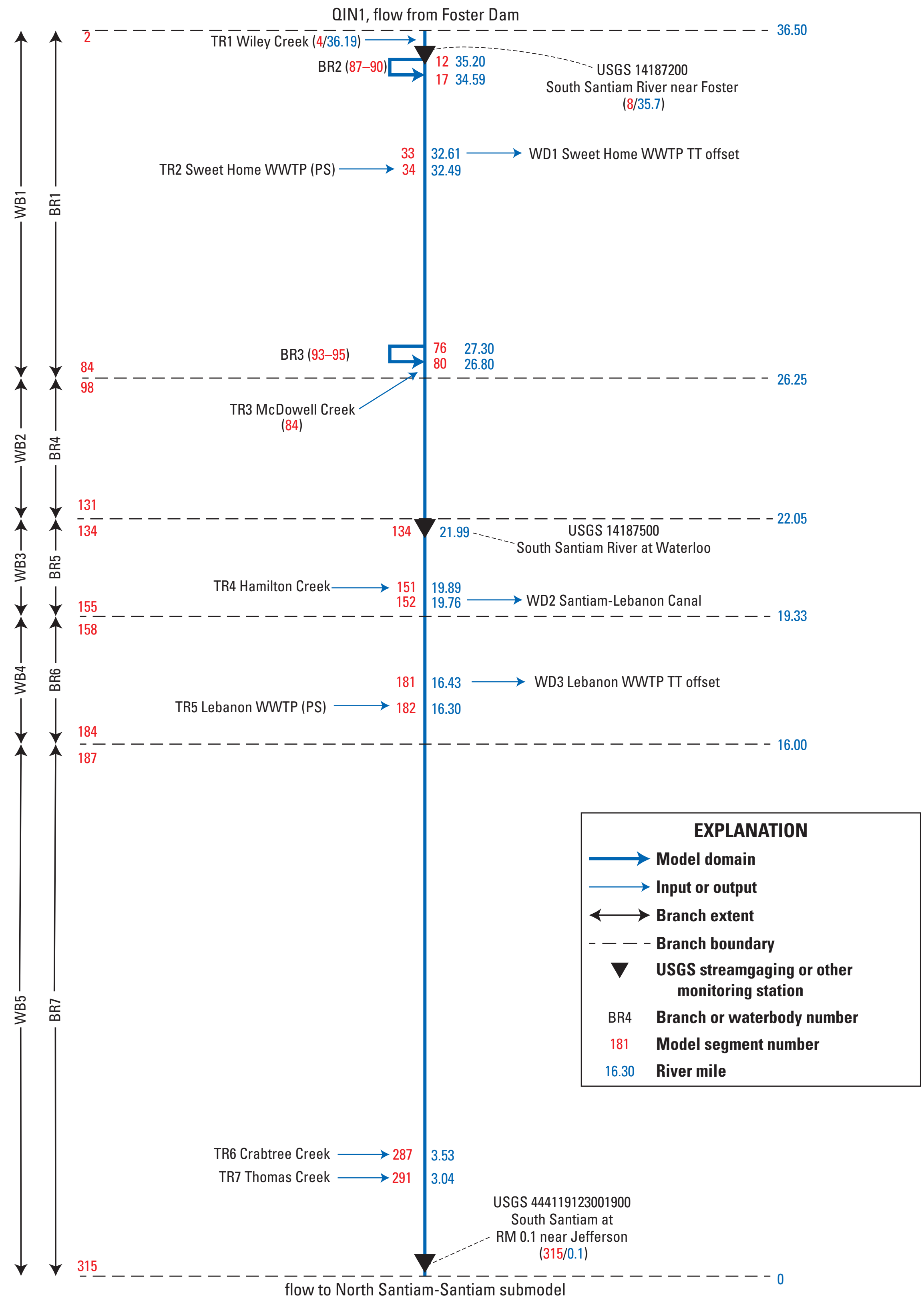


Figure 11. South Santiam River submodel, including locations of inflows, withdrawals, branch and waterbody boundaries; and USGS streamgaging stations or monitoring sites. Abbreviations: BR, branch; PS, point source; QIN, inflow; RM, river mile; TR, tributary; TT, travel time; WB, waterbody; USGS, U.S. Geological Survey; WD, withdrawal; WWTP, wastewater treatment plant.

Temporal Inputs

All data sources for temporal inputs to South Santiam River submodel are listed in table 1.

Meteorology

All waterbodies in the South Santiam River submodel use the same meteorological data. In the original model, data from the Stayton RAWS site were used (Bloom, 2016). This RAWS meteorological station was no longer active by 2016. Instead, data were sourced from the Jordan RAWS site, located approximately 9 miles southeast of the old Stayton RAWS site and 270 ft higher in elevation. Model calibration and sensitivity analyses indicated that stream temperatures estimated by the South Santiam River submodel on the basis of reported air temperatures from the Jordan RAWS site appeared to be biased low by as much as several degrees Celsius. Efforts to improve model fit included trials with a wide range of possible parameter adjustments. Ultimately, universally increasing the air-temperature input to the model by 2 °C was selected as the simplest approach that yielded a model fit with MAE close to or within 1 °C when compared to the estimated water temperatures from USGS station 444113123001900 (South Santiam River at RM 0.1 near Jefferson), depending on the model year (table 3). This adjustment suggests that the South Santiam River submodel may not capture channel complexities and width-to-depth ratios adequately to reproduce accurate surface energy fluxes, but a detailed improvement to the bathymetry of the submodel was beyond the scope of this investigation. Model fit is discussed in greater detail in section “South Santam River submodel: Model Fit: Temperature.” In the original model, cloud cover and solar radiation data from different sources were applied, depending on the model year. In this model update, cloud cover data were assigned from reported values at the Eugene Airport (Mahlon Sweet Field), as converted to units for CE-QUAL-W2 as described in section “Methods and Data: Updating of Model Parameters and Inputs: Boundary Conditions.” Solar radiation data were applied from the University of Oregon SRML in Eugene.

Flow

Measured flow inputs to the South Santiam River submodel included data from USGS station 14187000 (Wiley Creek near Foster) and USGS station 14188800 (Thomas Creek near Scio). Where measured data were unavailable, streamflow was estimated using several methods. The upstream-most streamgaging station on the South Santiam River within the model domain is USGS station 14187200 (South Santiam River near Foster). This streamgaging station is downstream of the inflow from Wiley Creek (USGS station 14187000), which in turn is directly downstream of Foster Dam. Streamflow input from Foster Dam to branch 1 was thus estimated by subtracting the Wiley Creek flow from the South Santiam River flow measured at USGS station 14187200. Measured flow data were not available for model tributaries representing McDowell, Hamilton, and Crabtree Creeks. Streamflow inputs from McDowell and Hamilton Creeks were estimated using a watershed ratio method, whereas flow in Crabtree Creek, for which an historical record was available, was estimated using a regression-based approach. Streamflow in McDowell Creek was estimated according to the equation:

$$Q_{McDowell} = \left(\frac{24.1}{51.8}\right) * Q_{14187000} \tag{18}$$

where

$Q_{McDowell}$ is estimated streamflow in McDowell Creek, in cubic meters per second; and

$Q_{14187000}$ is streamflow as measured at USGS station 14187000, Wiley Creek near Foster, in cubic meters per second.

The ratio in equation 18 represents the watershed area of McDowell Creek divided by the watershed area of Wiley Creek. Streamflow in Hamilton Creek was estimated according to the equation:

$$Q_{Hamilton} = \left(\frac{40.1}{51.8}\right) * Q_{14187000} \tag{19}$$

where

$Q_{Hamilton}$ is estimated streamflow in Hamilton Creek, in cubic meters per second; and

$Q_{14187000}$ is measured streamflow at USGS station 14187000, Wiley Creek near Foster, in cubic meters per second.

The ratio in equation 19 represents the watershed area of Hamilton Creek divided by the watershed area of Wiley Creek.

Streamflow in Crabtree Creek was estimated using a regression between flows measured at USGS station 14188800 (Thomas Creek near Scio) and flows measured at USGS station 14188700 (Crabtree Creek near Crabtree; data available from 1963 to 1970) according to the equation:

$$Q_{Crabtree} = 10^{(0.234+0.9114*\log_{10}Q_{14188800})} \tag{20}$$

where

$Q_{Crabtree}$ is estimated streamflow in Crabtree Creek at the site of historical USGS station 14188700, in cubic meters per second; and

$Q_{14188800}$ is measured streamflow at USGS station 14188800, Thomas Creek near Scio, in cubic meters per second.

Point sources to the South Santiam River submodel include WWTPs for the cities of Lebanon and Sweet Home. Discharge rates used for the 2011, 2015, and 2016 models were not updated from those reported by Bloom (2016).

The original version of the South Santiam River submodel included many small withdrawals (Bloom, 2016), but only the three largest were included in the updated model, due to the difficulty of obtaining updated withdrawal data and the discontinuation of some withdrawals. Withdrawals to the Lebanon Santiam Canal were monitored at USGS station 14187600 (Lebanon Santiam Canal near Lebanon). The other two withdrawals are travel-time offsets for the point sources representing the City of Sweet Home and City of Lebanon WWTPs.

Water Temperature

Water temperature inputs for the upper boundary of the South Santiam River submodel utilized data from USGS station 14187200, South Santiam River near Foster. For Wiley Creek, temperature measurements from USGS station 14185000 (South Santiam River below Cascadia), which is located on the South Santiam River upstream of Foster Lake and thus records water temperatures not influenced by Foster Lake or by releases from Green Peter Dam, were used as a proxy. Temperatures for McDowell, Hamilton, Crabtree, and Thomas Creeks were estimated using multiple linear regressions developed from water temperature measurements collected during the initial development of the South Santiam River submodel and from other continuous stream temperature datasets available for 2011, 2015, and 2016. These relations were developed using stepwise regressions with Akaike Information Criteria (stepAIC; see Venables and Ripley, 2002) to identify the best model fit using water temperature data from temperature-monitoring stations throughout the Willamette River Basin. Despite limitations on the seasonal extent of the data available in the early 2000s to support the initial development of the regression models, sensitivity analyses showed that this approach yielded better goodness-of-fit statistics for the South Santiam River submodel temperatures than applying proxy records from other drainages, as was utilized for Wiley Creek.

The temperature of McDowell Creek was estimated as:

$$T_{McDowell} = 0.46 * T_{14211550} + 0.04 * T_{14192015} + 0.46 * T_{453004122510301} \tag{21}$$

where

$T_{McDowell}$ is estimated water temperature in McDowell Creek, based on data from LASAR site 23778, in degrees Celsius;

$T_{14211550}$ is measured water temperature at USGS station 14211550, Johnson Creek at Milwaukie, in degrees Celsius;

$T_{14192015}$ is measured water temperature at USGS station 14192015, Willamette River at Keizer, in degrees Celsius; and

$T_{453004122510301}$ is measured water temperature at USGS station 4533004122510301, Beaverton Creek at 170th Ave in Beaverton, in degrees Celsius.

The temperature of Hamilton Creek was estimated as:

$$T_{Hamilton} = 1.05 * T_{14211550} \tag{22}$$

where

$T_{Hamilton}$ is estimated water temperature in Hamilton Creek, based on data from LASAR site 11419, in degrees Celsius; and

$T_{14211550}$ is measured water temperature at USGS station 14211550, Johnson Creek at Milwaukie, in degrees Celsius.

The water temperature of Crabtree Creek was estimated as:

$$T_{Crabtree} = -0.02 * T_{14211550} + 0.36 * T_{14192015} + 0.97 * T_{453040123065201} - 0.24 * T_{453004122510301} \tag{23}$$

where

$T_{Crabtree}$ is estimated water temperature in Crabtree Creek, based on data from LASAR site 10784, in degrees Celsius;

$T_{14211550}$ is measured water temperature at USGS station 14211550, Johnson Creek at Milwaukie, in degrees Celsius;

$T_{14192015}$ is measured water temperature at USGS station 14192015, Willamette River at Keizer, in degrees Celsius;

$T_{453040123065201}$ is measured water temperature at USGS station 453040123065201, Gales Creek at Old Highway 47 in Forest Grove, in degrees Celsius; and

$T_{453004122510301}$ is measured water temperature at USGS station 4533004122510301, Beaverton Creek at 170th Ave in Beaverton, in degrees Celsius.

The temperature of Thomas Creek was estimated as:

$$T_{Thomas} = 1.13 * T_{14211550} \tag{24}$$

where

T_{Thomas} is estimated water temperature in Thomas Creek, based on data from LASAR site 10783, in degrees Celsius; and

$T_{14211550}$ is measured water temperature at USGS station 14211550, Johnson Creek at Milwaukie, in degrees Celsius.

The water temperature of point sources included in the South Santiam River submodel were not updated from the original values applied by Bloom (2016). The temperature of distributed tributaries for branches 1 through 5 was assigned to be identical to data from USGS station 14185000, South Santiam River below Cascadia. The temperature of distributed tributaries 6 and 7 was estimated as a weighted average of the estimated temperature of Crabtree Creek (50 percent) and groundwater assumed to have a constant temperature of 11.5 °C (50 percent).

Model Fit

Water Balance

In the South Santiam River submodel, distributed tributaries were activated for all seven model branches. Distributed flow in branches 1–4 was estimated by comparing modeled flow at segment 134 with measured flow at USGS station 14187500, South Santiam River at Waterloo, and apportioning the difference among the four branches upstream. Distributed flow in branches 5–7 was estimated by comparing the modeled outflow from the South Santiam River submodel at segment 315 to estimated flows at USGS station 444119123001900, South Santiam River at RM 0.1 near Jefferson, a "virtual station" where the streamflow is estimated as the difference between measured flows in the Santiam River at Jefferson (USGS station 14189000) and the North Santiam River at Greens Bridge (USGS station 14184100). Distributed tributary flows were initially set to zero, then estimated iteratively by comparing measured and modeled streamflow and adding the smoothed difference, divided by the number of branches between streamgage locations to the previous distributed tributary flow, until a reasonable model fit was achieved as determined from a time series plot of the measured versus modeled streamflow at locations where data were available. A comparison of modeled and measured streamflows for the final South Santiam River submodel shows good agreement (fig. 12).

Water Temperature

Only one continuous water temperature dataset was available to check the fit of the South Santiam River submodel in 2011, 2015, and 2016, at RM 0.1 near the confluence of the North and South Santiam Rivers (fig. 11). That station is a "virtual station," not a real measurement station. Streamflow at that site is estimated by subtracting the streamflow in the North Santiam River at Greens Bridge (USGS station 14184100) from the streamflow in the Santiam River at Jefferson (USGS station 14189000). Water temperature at the mouth of the South Santiam River is then estimated with a mass and energy balance, such that the estimated temperature is given by:

$$T_{SSantiam} = \frac{((Q_{Santiam} * T_{Santiam}) - (Q_{NSantiam} * T_{NSantiam}))}{(Q_{Santiam} - Q_{NSantiam})} \tag{25}$$

where

$T_{SSantiam}$ is estimated water temperature in the South Santiam River at its mouth, in degrees Celsius;

$Q_{Santiam}$ is measured streamflow at USGS station 14189000, Santiam River at Jefferson, in cubic meters per second;

$T_{Santiam}$ is measured water temperature at USGS station 14189050, Santiam River near Jefferson, in degrees Celsius;

$Q_{NSantiam}$ is measured streamflow at USGS station 14184100, North Santiam River at Greens Bridge, in cubic meters per second; and

$T_{NSantiam}$ is measured water temperature at USGS station 14184100, North Santiam River at Greens Bridge, in degrees Celsius.

Although the water temperature estimated using equation 25 is useful as a quick estimate of the water temperature near the mouth of the South Santiam River, and provides some useful patterns in the estimated data tied to seasonal changes and weather variations, this mass and energy balance does not account for other small ungaged sources of water and heat (such as the City of Jefferson WWTP input), and in particular does not account for the flux of environmental energy that often warms this reach of the North Santiam and Santiam Rivers between the temperature-measurement stations. As a result, any unaccounted-for environmental heating of the river is manifested as a (potentially substantial) positive bias in the estimated water temperature in the South Santiam River.

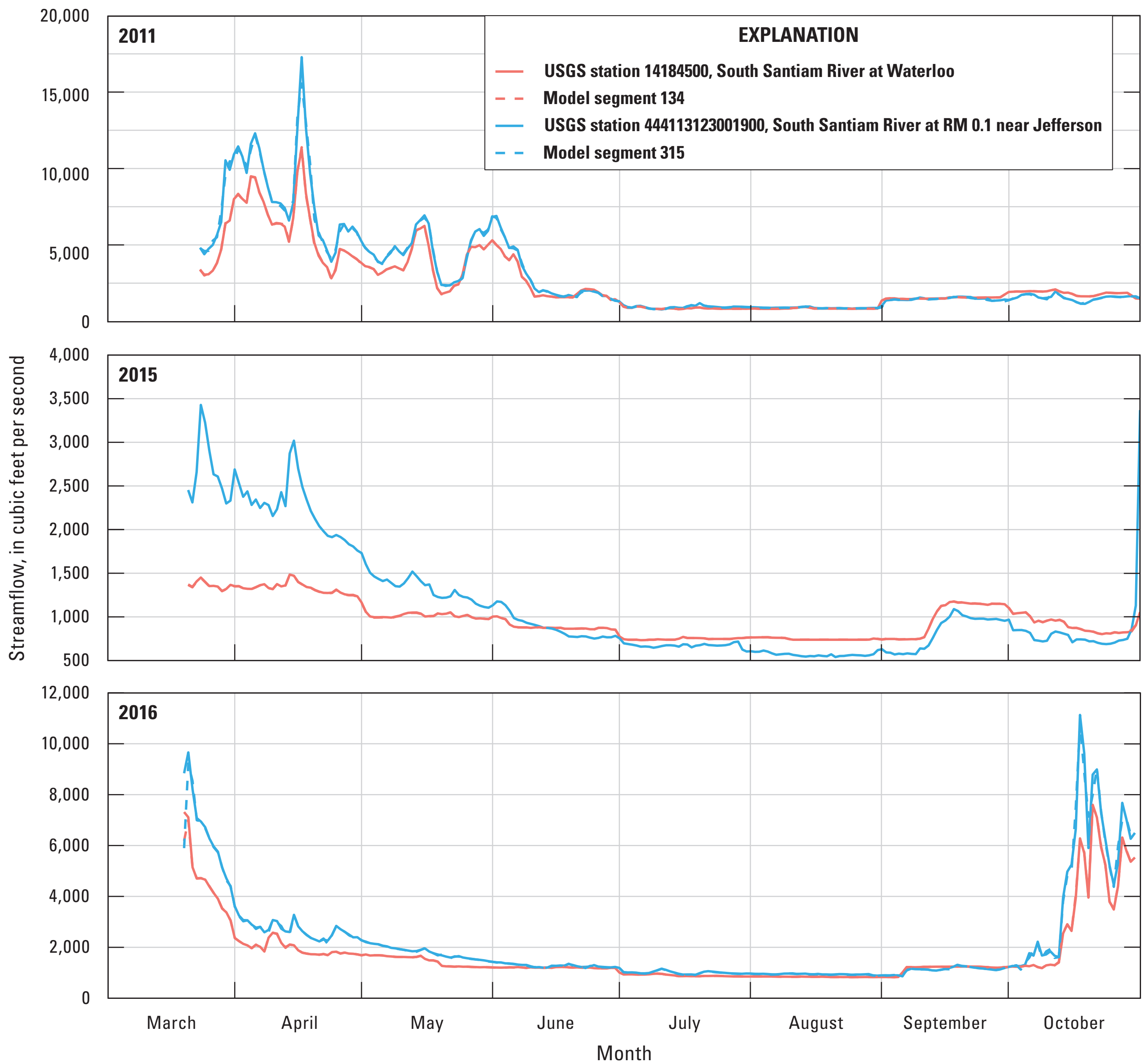


Figure 12. Daily modeled streamflow in 2011, 2015, and 2016 from the South Santiam River submodel at segments 134 and 315, measured streamflow at U.S. Geological Survey (USGS) station 14184500 (South Santiam River near Waterloo), and estimated streamflow at USGS station 444113123001900 (South Santiam River at river mile [RM] 0.1 near Jefferson), northwestern Oregon. Where not visible, dashed lines are plotted directly over solid lines.

Comparison of modeled water temperatures from segment 315 (the downstream outflow of the South Santiam River submodel) with the estimated water temperatures at USGS virtual station 444113123001900 shows that the South Santiam River submodel temperatures tend to be cooler than the estimated stream temperatures from the virtual station, with an overall MAE between 0.77 °C (2016) and 1.21 °C (2011; table 3), and a strong negative bias as expressed in the mean error (ME). It is not known whether this apparent bias is due to the submodel producing temperatures that are too cool, or the estimation method from the virtual station producing temperatures that are known to be too warm in summer, or a combination of both. Many combinations of boundary condition adjustments were evaluated to test whether a better fit could be obtained; ultimately, adding 2 °C to the model air temperature input achieved the best result, as shown in figure 13, but it would be best to directly monitor the temperature of the South Santiam River near its mouth in the future to resolve this uncertainty. Improvements to the South Santiam River submodel, through a comprehensive readjustment of the model bathymetry or other parameters, may be possible in the future, but was beyond the scope of this study. Given the uncertainty in the estimated water temperatures from the virtual station, the real test of performance for the South Santiam River submodel is to evaluate model goodness-of-fit farther downstream in the Santiam River, using the North Santiam and Santiam River submodel, to which the South Santiam River submodel provides input.

North Santiam and Santiam River Submodel

Reach Description

The North Santiam River, a major tributary to the Santiam River, drains about 730 mi^2 of the foothills and upper elevations of the Cascade Range in the eastern Willamette River Basin (Branscomb and others, 2002; U.S. Geological Survey, 2020c). Elevations in the basin range from approximately 10,500 ft at the summit of Mount Jefferson to about 220 ft at its confluence with the South Santiam River; the basin receives an average of 83 inches of precipitation annually (U.S. Geological Survey, 2020c). The upper reach of the North Santiam River is dammed by Detroit Dam, a large water storage and power-generating facility, and by Big Cliff Dam immediately downstream of Detroit Dam, which operates primarily as a re-regulation dam to smooth variable outflows from Detroit Dam (Sullivan and Rounds, 2004).

Upstream of Detroit Dam, the North Santiam and Breitenbush Rivers drain permeable, young, fractured basaltic terrane of the High Cascades geologic province, which supplies stable groundwater flows to the river from a system of spring complexes. Blowout Creek, which enters Detroit Lake above Detroit Dam, and the Little North Santiam River and other tributaries entering the North Santiam River downstream of Big Cliff Dam, drain the less permeable and steeper terrane of the Western Cascades geologic province and tend to respond more strongly to storm inputs (Risley and others, 2012). The North Santiam River is the steepest of the USACE-dammed tributaries to the Willamette River, with a gradient as high as 1 percent in the reaches immediately below Big Cliff Dam and an average gradient of 0.28 percent (Risley and others, 2012; Wallick and others, 2013). Relative to other USACE-dammed tributaries to the Willamette River that have substantial bank stabilization in their lower reaches, the lower North Santiam River has segments that remain laterally dynamic, with active meander migration and avulsions downstream of Stayton. The City of Salem withdraws water from the North Santiam River at Geren Island near Stayton.

The Santiam River is formed by the confluence of the North and South Santiam Rivers about 12 miles upstream of its confluence with the Willamette River downstream of Albany. The Santiam River Basin drains about 1,810 mi^2 and receives an average of 78 inches of precipitation per year (Risley and others, 2012). The Santiam River flows in a wide, unconstrained floodplain that is underlain primarily by Quaternary alluvial deposits and is heavily cultivated (Sullivan and Rounds, 2004; Risley and others, 2012; Wallick and others, 2013).

Model Domain

The North Santiam and Santiam River submodel includes the North Santiam River downstream of Big Cliff Dam to its confluence with the South Santiam River, and the Santiam River from its start at the confluence of the North and South Santiam Rivers to its confluence with the Willamette River (fig. 14). The submodel comprises six waterbodies and six branches. No side channels are modeled. Three tributaries, two point sources, and nine withdrawals are included in the model.

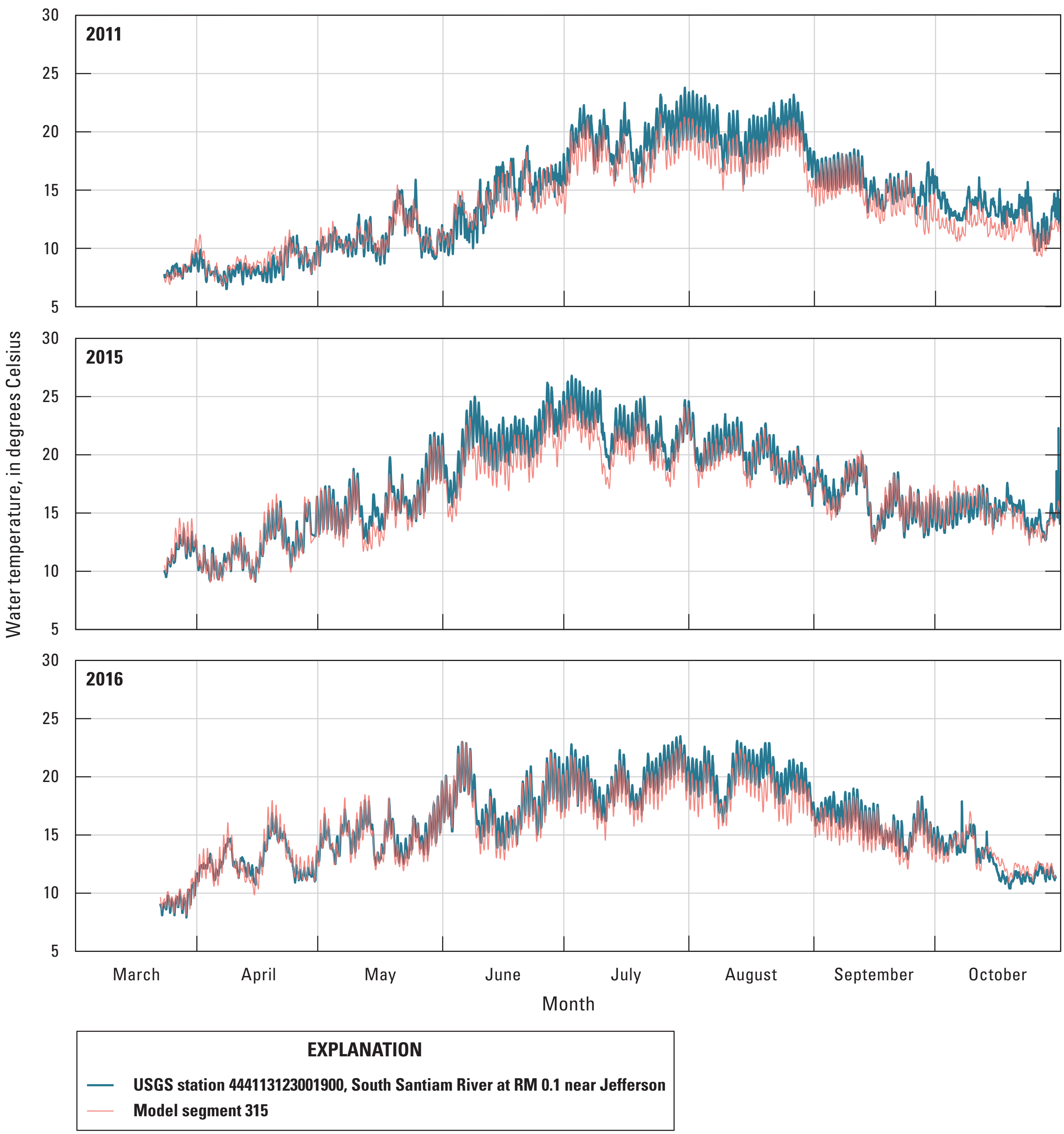


Figure 13. Subdaily simulated water temperature in 2011, 2015, and 2016 from the South Santiam River submodel at segment 315 and estimated water temperature at U.S. Geological Survey (USGS) virtual station 444113123001900 (South Santiam River at river mile [RM] 0.1 near Jefferson), northwestern Oregon.

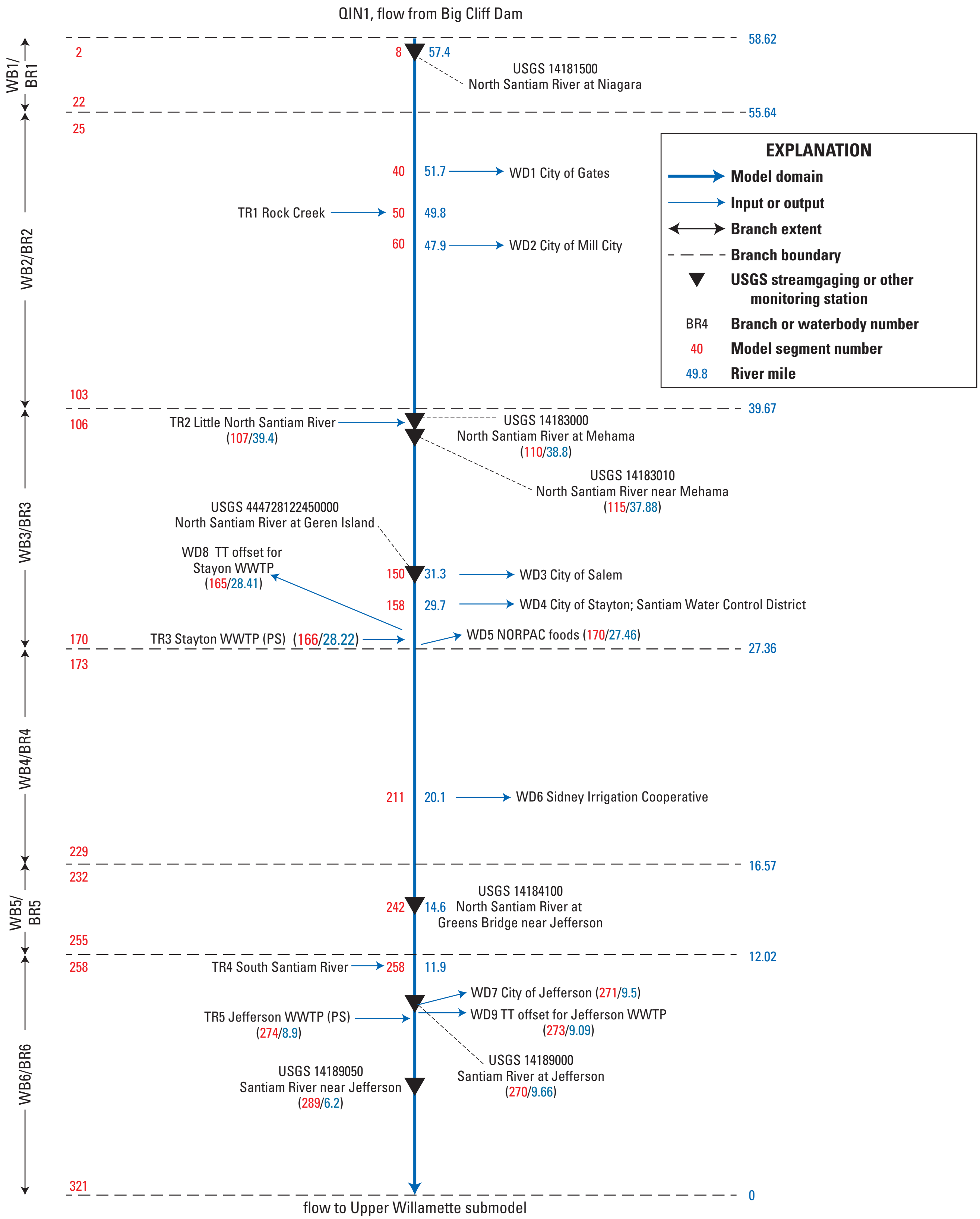


Figure 14. North Santiam and Santiam River submodel, including locations of inflows, withdrawals, branch and waterbody boundaries, and USGS streamgaging stations or monitoring sites. Abbreviations: BR, branch; PS, point source; QIN, inflow; TR, tributary; TT, travel time; USGS, U.S. Geological Survey; WB, waterbody; WD, withdrawal; WWTP, wastewater treatment plant.

Bathymetric Grid and Non-Temporal Parameters

No major changes were made to the bulk of the model grid in the updated model documented in this report; however, to improve model stability and decrease runtimes, many small adjustments were made to a number of parameters. As described earlier (see section, “Methods and Data: Updating of Model Parameters and Inputs: Model Grid and Structures”), CE-QUAL-W2 requires that the surface-layer index, a layer designation used by the model as a reference point for many of its calculations, be the same for each segment within a single waterbody. The original North Santiam and Santiam River submodel was configured with only one waterbody. In models with steep slopes like the North Santiam and Santiam submodel, however, the use of only one waterbody and a single surface-layer index meant that entire groups of segments in the model simulation commonly were “higher” in the grid than the surface-layer index, depending on flow conditions, which caused the model to run one-dimensionally and contributed to model instability. The original setup of the North Santiam and Santiam River submodel addressed this problem in part by adding narrow (0.1 m) cells to the bottom of problematic segments in the model grid (Sullivan and Rounds, 2004). This fix had a negligible effect on the water volume or residence time and allowed the model to successfully run to completion, but the model ran very slowly and was still prone to instabilities, particularly during high- or low-flow conditions.

To address the stability and runtime issues, several changes to the model grid were made with this update. First, the slope of branch 1 was decreased from 0.00790 to 0.00500, which did not substantively change the results or the characteristics of the model’s representation of that reach but improved model stability. Second, each of the six model branches was separated into its own waterbody, thus allowing each branch to be modeled with its own surface-layer index. Breaking the model grid into multiple waterbodies, combined with better algorithms in the updated model version that allow the river bottom to be artificially lowered when necessary, made many of the artificial 0.1-m cells unnecessary and allowed more than 750 of these artificial cells to be removed. Third, sensitivity testing showed that certain cells in the grid were constraining the maximum allowable time step, most often where a relatively narrow cell was receiving substantial flow from a wider cell immediately upstream, thus creating “pinch points” in moving water downstream and causing water to “mound up” upstream and potentially produce a numerical instability. Smoothing these cell-width differences by making small adjustments to these cell widths, and adjusting the friction coefficient, as necessary, eliminated these pinch points and allowed the model to run faster. Running the model faster, however, also introduced new instabilities under certain conditions. Testing showed that adding artificial model spillways between each branch tended to reduce the number and frequency of these instabilities, isolating any water-surface oscillations by changing the branch-to-branch boundary conditions from an internal head boundary condition to an internal flow boundary condition. Finally, CE-QUAL-W2 allows the user to select the algorithm used to calculate vertical turbulence in the horizontal momentum equation, with the best choice dependent on stability constraints and whether the system is friction-shear dominated (typically, riverine models) or wind-shear dominated (typically, reservoir or lake models; see Wells, 2019 for further discussion). By changing the turbulence closure scheme from “W2” (wind-shear) to “NICK” (friction-shear) or “W2N” (wind-shear with modified mixing length) in several branches, as guided by a sensitivity analysis, model stability was further increased.

The shading values applied to the North Santiam and Santiam River submodel represent “current conditions,” as documented in Sullivan and Rounds (2004), but the canopy top elevations in branch 1 of the shade-parameter input file were reduced to account for the lower slope applied to branch 1.

Temporal Inputs

All data sources for temporal inputs to the North Santiam and Santiam River submodel are listed in table 1.

Meteorology

All waterbodies in the North Santiam and Santiam River submodel used the same meteorological data inputs. Air temperature, dew-point temperature, wind speed, and wind direction data were sourced from the Stayton RAWS site in the original 2001-2002 models. However, the Stayton RAWS site had been decommissioned by 2011. These data were replaced with data from the Jordan RAWS site, located approximately 9 miles southeast of the Stayton RAWS site and 270 ft higher in elevation. Cloud cover was converted to CE-QUAL-W2 units from reported values at the Eugene Airport (Mahlon Sweet Field), as described in section “Methods and Data: Updating of Model Parameters and Inputs: Boundary Conditions.” The original version of the model used cloud cover values based on the difference between observed and theoretical solar radiation (Sullivan and Rounds, 2004); a sensitivity analysis showed that the difference between the methods had a negligible effect on stream temperatures. Observed values were applied for consistency across models and to remove the need to interpolate cloud cover during nighttime hours. Solar radiation data were sourced from the University of Oregon SRML Eugene station. Dew-point temperature was calculated on the basis of measured relative humidity using the “weathermetrics” package in R, which follows the methodology established by NOAA (Anderson and others, 2016). All meteorological data were averaged to an hourly frequency and, where necessary, interpolated to the top of the hour.

Flow

Flows entering the North Santiam and Santiam River submodel include releases from Big Cliff Dam and flow from three tributaries (Rock Creek, Little North Santiam River, and South Santiam River), two point sources, and six distributed tributaries. Measured data were available for inflow to the upstream boundary of the model from USGS streamgaging station 14181500 (North Santiam River at Niagara). Streamflow data for Rock Creek were not available for 2011, 2015, or 2016; however, a streamgaging station operated on Rock Creek from October 2005 to October 2008 (USGS station 14181750, Rock Creek near Mill City). These data were used to build a logarithmic regression relation with data from the Little North Santiam River:

$$Q_{Rock} = 10^{(-1.31+1.10*\log_{10}(Q_{14182500}))} \qquad (26)$$

where

Q_{Rock} is estimated streamflow in Rock Creek, in cubic meters per second; and

$Q_{14182500}$ is measured streamflow at USGS station 14182500, Little North Santiam River near Mehama, in cubic meters per second.

Streamflow data for the Little North Santiam River were available from USGS station 14182500 (Little North Santiam River near Mehama). Tributary flow into the North Santiam and Santiam River submodel was available at half-hourly or shorter intervals; for input to the model, only values on the hour were used. Streamflow from the South Santiam River was simulated by the South Santiam River submodel.

Point source inflows to the model included effluent from the Stayton and Jefferson municipal WWTPs. Discharge rates for these point sources were unchanged from those used in the original model (Sullivan and Rounds, 2004).

Nine withdrawals from the North Santiam or Santiam Rivers were included in the submodel. These include withdrawals for the Cities of Gates, Mill City, Salem, and Stayton; NORPAC and the Sidney Irrigation Cooperative; the City of Jefferson, and artificial travel-time offset withdrawals for the Stayton and Jefferson WWTPs. All withdrawals included in the North Santiam and Santiam River submodel used 2001 flow-rate estimates except those for the City of Salem, for which updated data for 2011, 2015, and 2016 were provided by the City of Salem (J. Boyington and T. Sherman, City of Salem, written commun., 2016). Withdrawal rates were provided to the model at a monthly frequency.

Water Temperature

Measured water temperatures of stream inputs to the North Santiam and Santiam River submodel were available from USGS station 14181500 (North Santiam River at Niagara) for all years, and for the Little North Santiam River from USGS station 14182500 in 2011 and 2015. Other stream temperature inputs were estimated.

Inflow temperatures from the Little North Santiam River in 2016 were estimated using a regression between data from USGS station 14182500 (Little North Santiam near Mehama; temperature monitoring discontinued in December 2015) and USGS station 14185900 (Quartzville Creek near Cascadia):

$$T_{LittleNorth} = 1.134 * T_{14185900} - 0.2831 \qquad (27)$$

where

$T_{LittleNorth}$ is estimated water temperature in the Little North Santiam River, in degrees Celsius; and

$T_{14185900}$ is measured water temperature at USGS station 14185900, Quartzville Creek near Cascadia, in degrees Celsius.

Quartzville Creek is a tributary to Green Peter Lake on the Middle Santiam River; both Quartzville Creek and the Little North Santiam River drain impermeable rocks of the Western Cascades with little influence from groundwater springs. Both streams share a similar aspect and length.

No water temperature data for Rock Creek were available for 2011, 2015, or 2016; temperatures for Rock Creek were assigned to be identical to temperatures in the Little North Santiam River (measured in 2011 and 2015; estimated in 2016). The water temperature of the South Santiam River was modeled by the South Santiam River submodel.

The temperature assigned to the effluent from the Stayton and Jefferson WWTPs was unchanged from the 2001-2002 models (Sullivan and Rounds, 2004). The temperature of distributed tributaries for branches 1 through 3 and 6 was estimated using the temperature of the Little North Santiam River (measured or estimated) with a weighting of 70 percent along with 30 percent groundwater estimated as a constant 11.5 °C. The temperatures of distributed tributaries 4 and 5 were weighted as 60 percent from the temperature of the Little North Santiam River and 40 percent groundwater estimated as 11.5 °C.

Model Fit

Water Balance

Streamflow in the North Santiam and Santiam River submodel was calibrated using a water-budget analysis and the iterative assignment of flows in distributed tributaries in all branches, adjusted using three continuous streamgages within the modeling domain (table 2). Distributed tributary flow in branches 1 and 2 was calculated on the basis of measured streamflow at USGS station 14183000, North Santiam River at Mehama. Distributed tributary flow in branches 3 through 5 was calculated using measured streamflow at USGS station 14184100, North Santiam River at Greens Bridge. Distributed flow in branch 6 was calculated using measured streamflow from USGS station 14189000, Santiam River at Jefferson.

Comparisons between modeled and measured streamflows at these several sites showed good agreement after the distributed tributary flows were assigned (fig. 15).

The calibration of flow in the North Santiam and Santiam River submodel is somewhat different than in the original model (Sullivan and Rounds, 2004). The streamgaging station at Greens Bridge was installed in 2009, providing an additional streamgage within the model domain that was not available in 2001 or 2002. The distributed tributary flows for branches 1 and 2 generally add water during storms, indicating either the presence of a number of ungaged tributaries in the upper part of the modeled reach, or that the model was missing some overland flow. By contrast, the distributed tributaries in branches 3-5 tended to remove flow in summer; this appears to indicate a losing reach that was not evident when the original models were built and is only now recognized because of the availability of data from an additional streamgaging station.

Water Temperature

Continuous water temperature data were available at four locations in the North Santiam and Santiam River submodel domain for parts of the modeled period (table 3). In 2011 and 2015, output from segment 115 was compared to records from USGS station 14183010, North Santiam River near Mehama (fig. 16). This comparison shows a slight tendency for the model to overestimate diurnal variability in water temperature, but good reproduction of seasonal patterns, with a subdaily MAE of 0.41 and 0.56 °C in 2011 and 2015, respectively (table 3). Farther downstream at Geren Island near Stayton, simulated water temperatures were compared to data collected by USGS (station 444728122450000) in 2011 and by the City of Salem in 2015 and 2016. This comparison also revealed a tendency for the model to overestimate diurnal variability, but with good reproduction of overall patterns (fig. 17; table 3). Temperature data from USGS station 14184100 (North Santiam River at Greens Bridge) and USGS station 14189050 (Santiam River near Jefferson) were available for all three modeled years. The model shows a good fit compared to these data, with a subdaily MAE ranging from 0.45 to 0.94 °C, depending on the site and year (figs. 18 and 19; table 3). The Santiam River is known to have some amount of hyporheic flow (Hinkle and others, 2001), which can decrease the range of daily river temperatures. In the original development of the North Santiam and Santiam River submodel, Sullivan and Rounds (2004) noted the lack of a means to simulate such hyporheic flow in CE-QUAL-W2 and suggested that the unaccounted for hyporheic flow caused the North Santiam and Santiam River submodel to overestimate diurnal variation. This overestimated diurnal variation is still present, in some degree, for the results from 2011, 2015, and 2016 (fig. 19).

Upper Willamette River Submodel

Reach Description

The Upper Willamette River submodel comprises the upper Willamette River from RM 185.28, near Eugene, to RM 85.50 at Salem. From its confluence with the McKenzie River at RM 175.5 to about RM 132, near Corvallis, the upper Willamette River can be characterized as a “wandering gravel bed river,” with an active channel as wide as 2,300 ft (700 m), many secondary channels, and large, forested gravel bars (Church, 1988; Wallick and others, 2013). The upper Willamette River receives inflow from large rivers such as the Coast Fork Willamette, Middle Fork Willamette, McKenzie, and Santiam Rivers as well as several smaller tributaries, including the Long Tom, Marys, Calapooia, and Luckiamute Rivers. The Willamette River upstream of the Santiam River confluence is influenced by nine of the USACE Willamette Valley Project dams; all 13 of the Willamette Valley Project dams are influential downstream of the Santiam River confluence. The upper Willamette River thus integrates a wide range of climatic, geologic, and anthropogenic influences, including stable, snowmelt- and spring-driven flows from the High Cascades as well as flows from the steeper and more responsive, rain-fed Western Cascades and Coast Range streams.

Model Domain

The Upper Willamette River submodel comprises nine waterbodies, 13 branches, 15 tributaries, and eight withdrawals (fig. 20). Of the 15 tributaries included in the submodel, eight are point sources. Because CE-QUAL-W2 is laterally averaged and because bathymetric information was not available for all of its braided channels, representation of the upper Willamette River was simplified to a single channel. As configured here, the Upper Willamette River submodel receives flow from the Coast Fork and Middle Fork Willamette, McKenzie, and North Santiam and Santiam (including South Santiam farther upstream) River submodels. A model of the Long Tom River up to Fern Ridge Dam was originally developed by the Portland State University modeling group to simulate conditions occurring in 2001 and 2002, but that model was not used in this study; rather, the Long Tom River is treated as a tributary to the Upper Willamette River submodel.

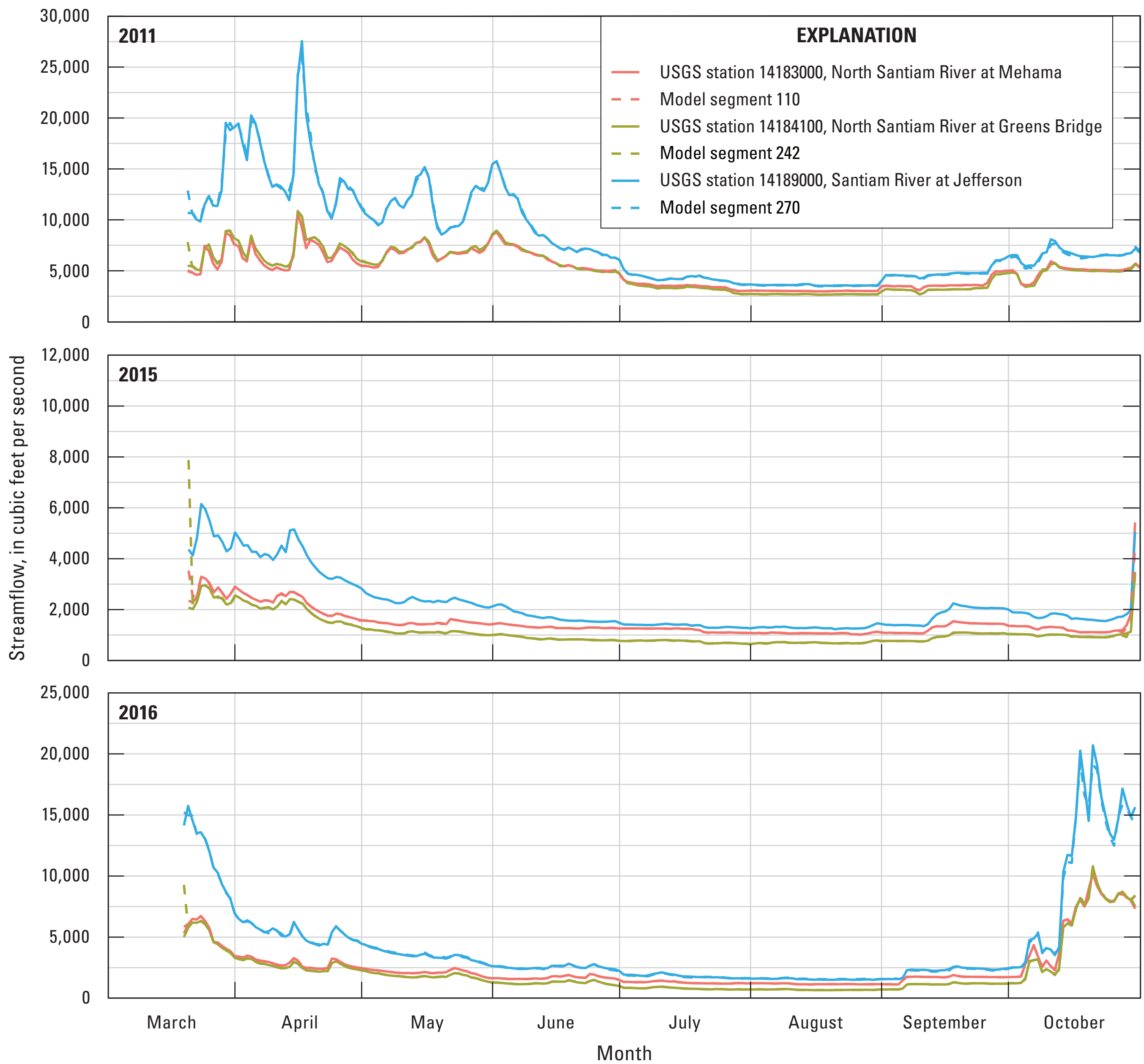


Figure 15. Daily modeled streamflow in 2011, 2015, and 2016 from the North Santiam and Santiam River submodel at segments 110, 242, and 270, and measured streamflow at U.S. Geological Survey (USGS) streamgaging stations 14183000 (North Santiam River at Mehama), 14184100 (North Santiam River at Greens Bridge), and 14189000 (Santiam River at Jefferson), northwestern Oregon. Where not visible, dashed lines are plotted directly over solid lines.

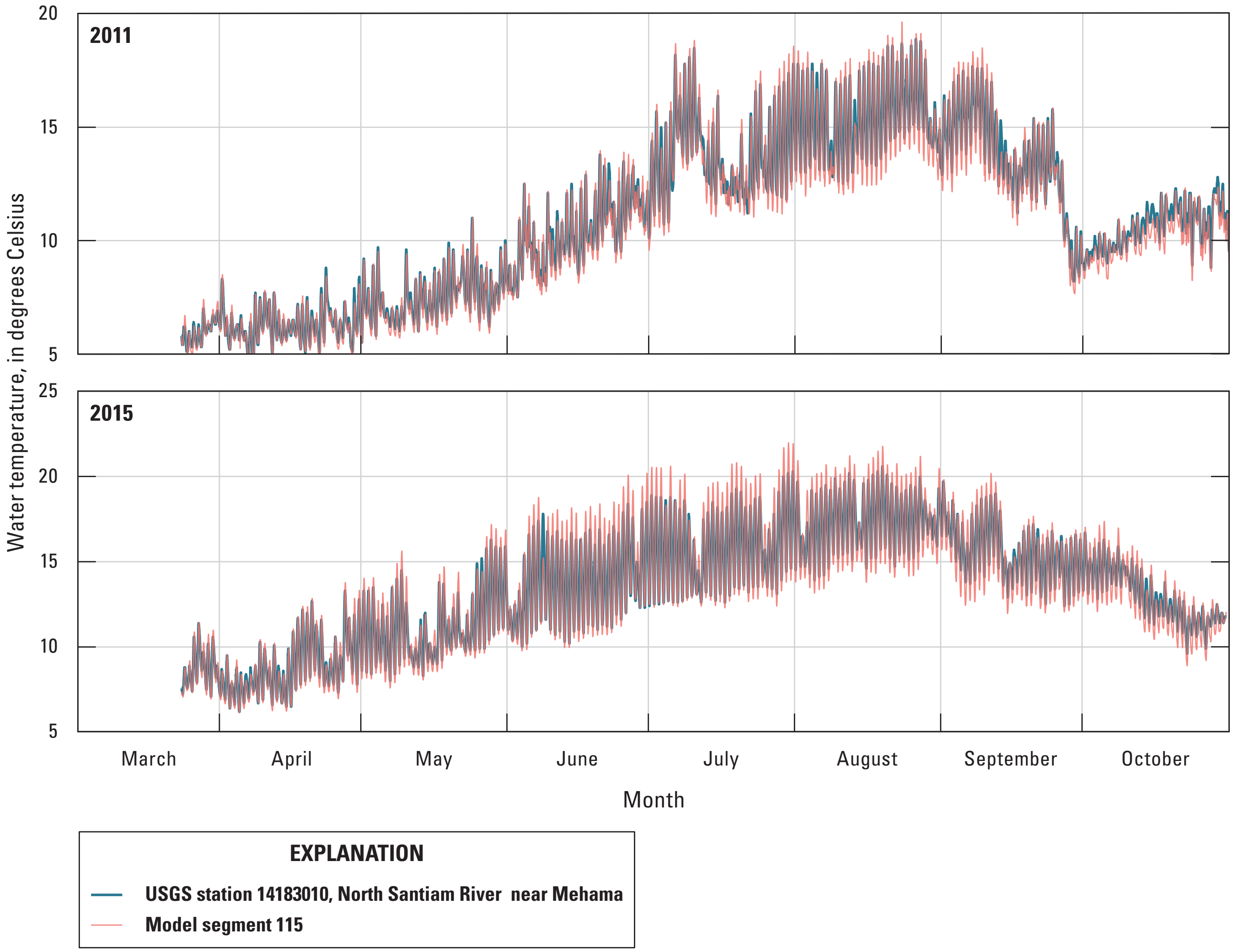


Figure 16. Subdaily modeled water temperature in 2011 and 2015 from the North Santiam and Santiam River submodel at segment 115, and measured water temperature at U.S. Geological Survey (USGS) station 14183010 (North Santiam River near Mehama), northwestern Oregon. No measured data were available for 2016.

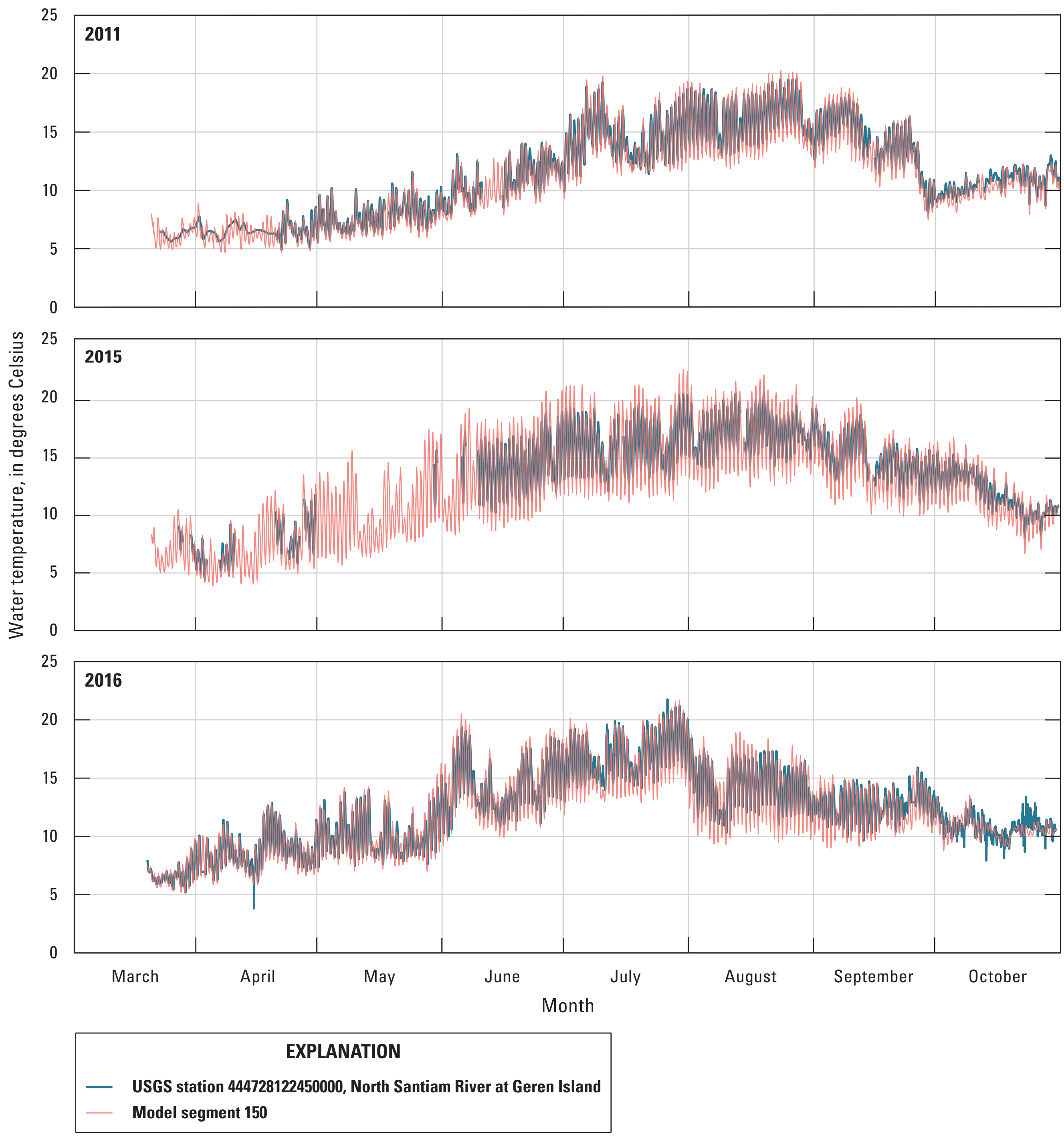


Figure 17. Subdaily modeled water temperature in 2011, 2015, and 2016 from the North Santiam and Santiam River submodel at segment 150, and measured water temperature at U.S. Geological Survey (USGS) station 444728122450000 (North Santiam River at Geren Island), northwestern Oregon. Data from 2011 were collected by USGS, and data from 2015 and 2016 were measured by the City of Salem.

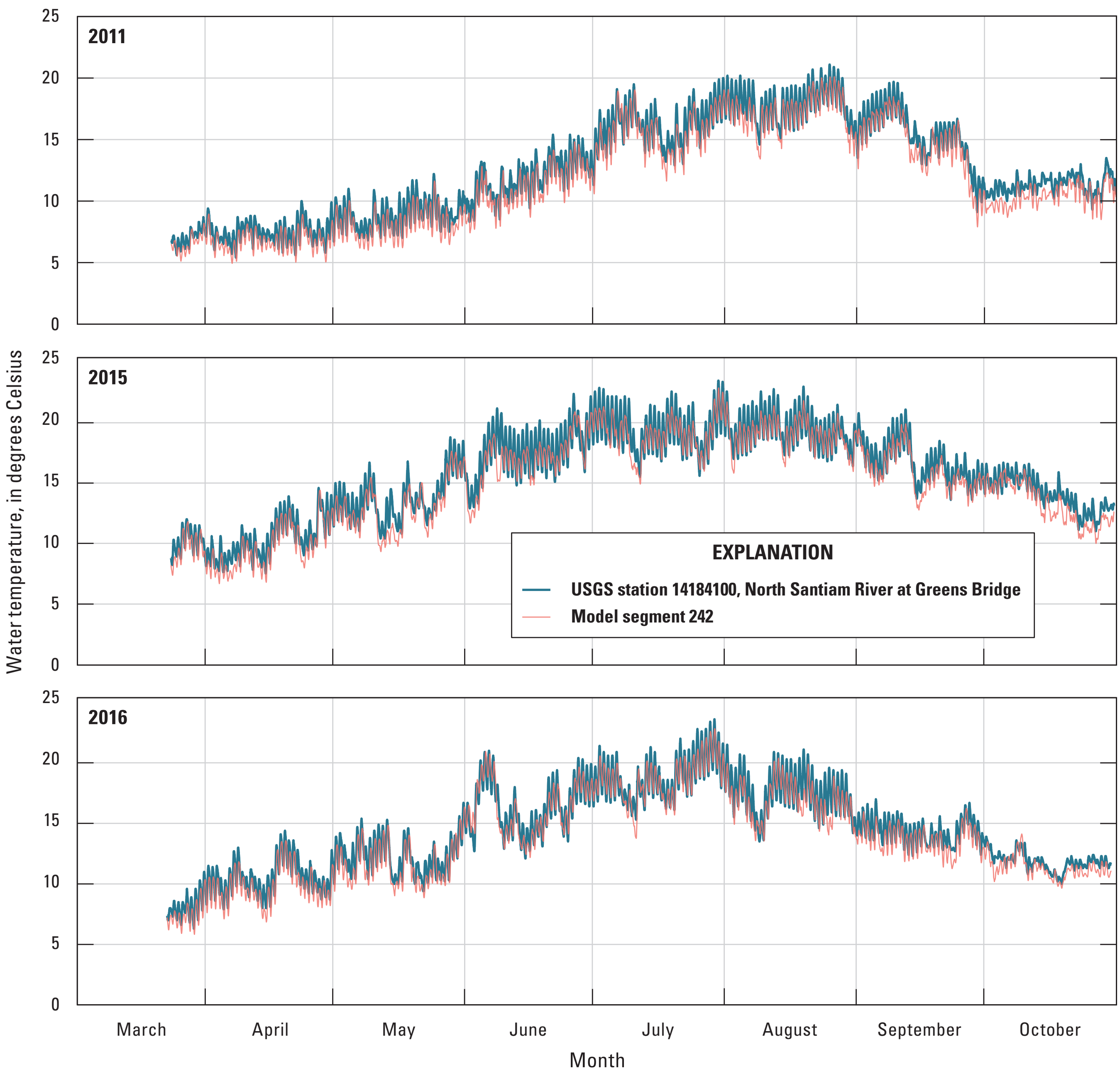


Figure 18. Subdaily modeled water temperature in 2011, 2015, and 2016 from the North Santiam and Santiam River submodel at segment 242, and measured water temperature at U.S. Geological Survey (USGS) station 14184100 (North Santiam River at Greens Bridge), northwestern Oregon.

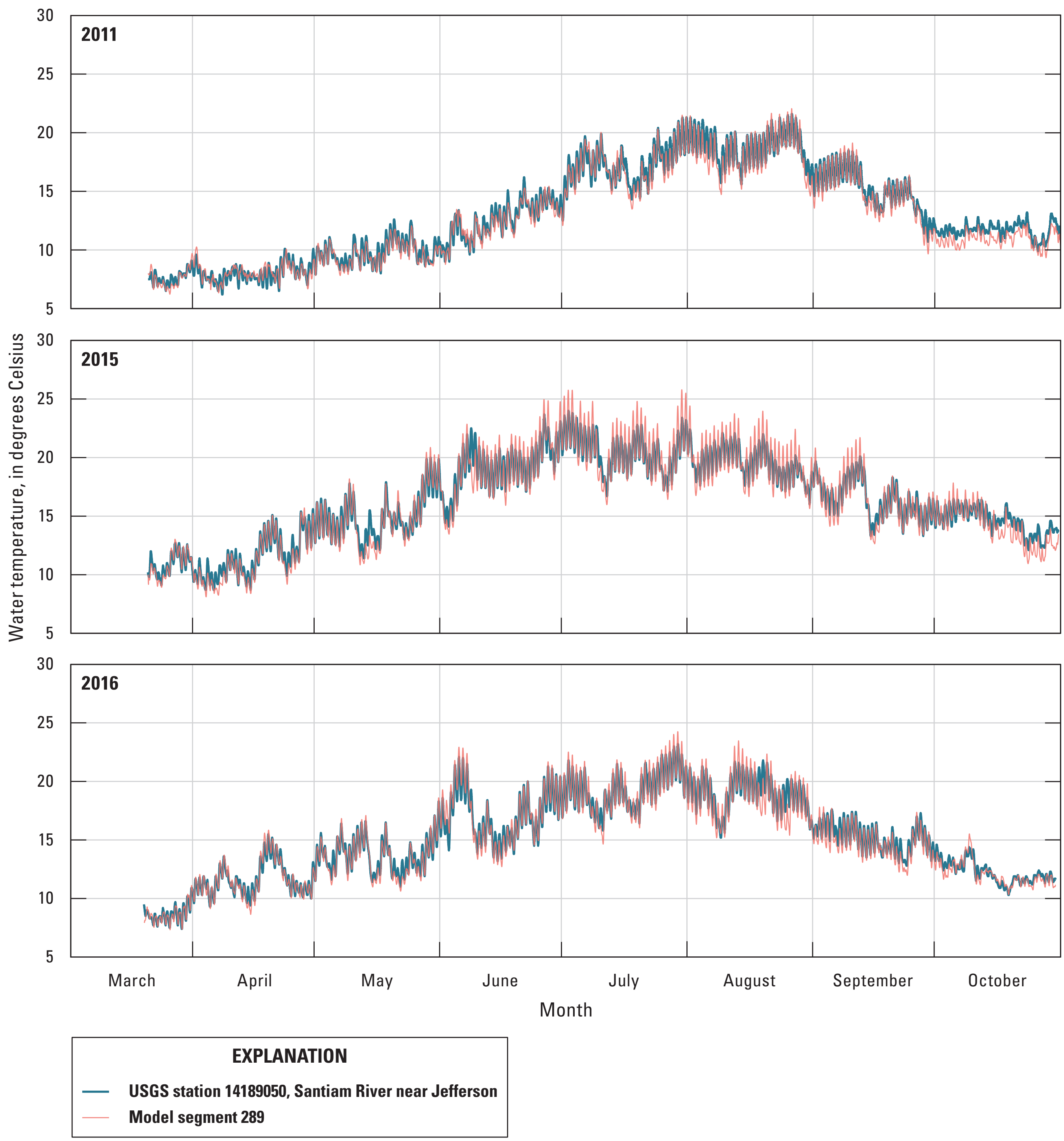


Figure 19. Subdaily modeled water temperature in 2011, 2015, and 2016 from the North Santiam and Santiam River submodel at segment 289, and measured water temperature at U.S. Geological Survey (USGS) station 14189050 (Santiam River near Jefferson), northwestern Oregon.

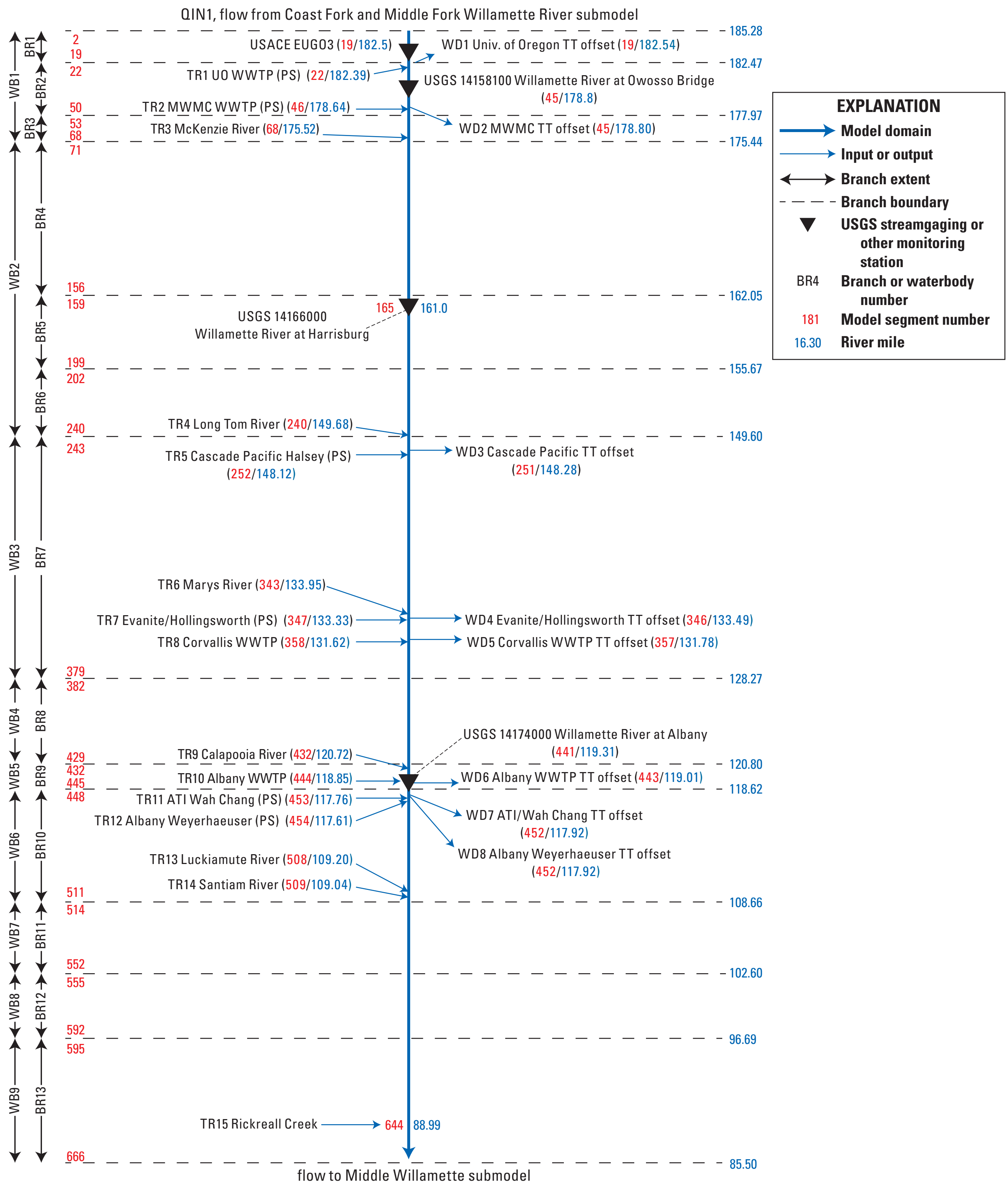


Figure 20. Diagram of the Upper Willamette River submodel, including locations of inflows, withdrawals, branch and waterbody boundaries, and USGS or other relevant streamgaging stations or monitoring sites. Abbreviations: BR, branch; MWMC, Metropolitan Wastewater Management Commission; PS, point source; QIN, inflow; TR, tributary; TT, travel time; USACE, U.S. Army Corps of Engineers; UO, University of Oregon; USGS, U.S. Geological Survey; WB, waterbody; WD, withdrawal; WWTP, wastewater treatment plant.

Bathymetric Grid and Non-Temporal Parameters

No substantive changes to the bathymetric grid were made for the update of this submodel.

Temporal Inputs

All data sources for temporal inputs to the Upper Willamette River submodel are listed in table 1.

Meteorology

Meteorological data for the Upper Willamette River submodel were sourced from Eugene Airport (Mahlon Sweet Field), the University of Oregon SRML in Eugene, Corvallis Municipal Airport, the Corvallis Agrimet station, Salem Municipal Airport (McNary Field), and the SRML site in Portland. For waterbodies 1 and 2, all meteorological data were from Eugene Airport (Mahlon Sweet Field) except for solar radiation, which was reported by the University of Oregon SRML site in Eugene. For waterbodies 3 through 6, air temperature, dew-point temperature, and solar radiation were sourced from the Corvallis Agrimet station, and cloud cover, wind speed, and wind direction were as reported from the Corvallis Municipal Airport. In 2011, days with missing cloud cover data were filled with reported cloud cover from the Salem Municipal Airport. Waterbodies 7 through 9 used meteorological data as reported by the Salem Municipal Airport, except for solar radiation, which was reported by the SRML site in Portland. Where Portland SRML data were missing, gaps were filled using data from the Eugene SRML site.

Flow

Upstream inflow along the Willamette River, from the McKenzie River, and from the Santiam River were from the Coast Fork and Middle Fork Willamette, McKenzie, and the North Santiam and Santiam River submodels, respectively. Measured streamflow data used as boundary conditions for tributaries included streamflow from the Long Tom River (USGS station 14170000), the Marys River (USGS station 14171000), and the Luckiamute River (USGS station 14190500).

Flows from the Calapooia River and Rickreall Creek were estimated. Streamflow from the Calapooia River, which was gaged from 1940 to 1981 (USGS station 14173500) was estimated using a log-transformed regression with data from the Pudding River at Aurora (USGS station 14202000):

$$Q_{Calapooia} = 10^{1.0721 * \log_{10}(Q_{14202000})} \tag{28}$$

where

$Q_{Calapooia}$ is estimated streamflow in the Calapooia River, in cubic meters per second; and

$Q_{14202000}$ is measured streamflow in the Pudding River at USGS station 14202000, in cubic meters per second.

No flow data for Rickreall Creek were available for 2001-2002, when the original models were developed, or for 2011, 2015, or 2016. Inflows from Rickreall Creek to the Upper Willamette River submodel were estimated using a watershed area approach and streamflow data from the Luckiamute River (USGS station 14190500) following Annear and others (2004):

$$Q_{Rickreall} = 0.533 * Q_{14190500} \tag{29}$$

where

$Q_{Rickreall}$ is estimated streamflow in Rickreall Creek, in cubic meters per second; and

$Q_{14190500}$ is measured streamflow in the Luckiamute River at USGS station 14190500, in cubic meters per second.

The coefficient in equation 29 represents the ratio between the watershed area of Rickreall Creek and the watershed area of the Luckiamute River at USGS station 14190500. Note that between the finalization of the models in this report and report publication, a record of flow in Rickreall Creek from USGS station 14190700 spanning 1957 to 1978 and from Oregon Water Resources Department station 14190800 spanning 1964 to 1985 was found. While the data from the latter station are not available from NWIS, they can be requested from the Oregon Water Resources Department. Future updates to the Upper Willamette River submodel may benefit from the development of a regression-based estimate of flow using these data rather than the watershed area approach used here.

The remaining tributaries to the Upper Willamette River submodel are point sources. Where available, point source discharge rates were updated using data from 2011, 2015, and 2016, as provided by ODEQ or obtained from the ECHO database. In some cases, data from 2016 were unavailable, so data from 2015 were used as a proxy. If no new data were available, values from the original models were applied. Since the development of the individual models for 2001-2002, several of these point sources have stopped discharging to the Willamette River. For simplicity, any non-discharging point sources were left in the submodel but were assigned a zero flow. By 2011, the University of Oregon heat plant (tributary 1) and the paper mill in Albany (tributary 12; operated most recently by International Paper) had been closed or stopped discharging to the river. By 2015, the Wah Chang/ATI (tributary 11) and Albany WWTP (tributary 10) had begun discharging water through a newly constructed joint “Talking Water Gardens” wetland; for modeling purposes, tributary 11 was assigned a zero flow in 2015 and 2016. All withdrawals included in the Upper Willamette River submodel are travel-time offsets for modeled point sources.

Water Temperature

The water temperature of inflows from the McKenzie River, and from the Santiam River, was passed to the Upper Willamette River submodel from other submodels. The temperature of all non-modeled tributary inputs to the Upper Willamette River submodel were estimated, generally using a multiple linear regression approach with other monitoring stations in the Willamette River Basin. Water temperature in the Long Tom River was estimated using data from USGS station 14170000 (Long Tom River at Monroe) after applying a 0.2 °C/mi warming rate applied for 6.8 miles and a time lag of 0.169 days; this general summertime warming rate is based on data and modeling from other studies to represent natural warming from a gaged location to the point of entry to the model (Rounds, 2010). Temperature in the Marys River was estimated using a multiple linear regression with data collected in summer of 2015 (Mamoon, 2016) and several USGS monitoring stations according to the equation:

$$T_{Marys} = 0.340 * T_{14211550} - 0.260 * T_{14192015} + 0.250 * T_{14152000} + 0.730 * T_{453040123065201} \quad (30)$$

where

T_{Marys} is estimated water temperature in the Marys River, in degrees Celsius;

$T_{14211550}$ is measured water temperature at USGS station 14211550, Johnson Creek at Milwaukie, in degrees Celsius;

$T_{14192015}$ is measured water temperature at USGS station 14192015, Willamette River at Keizer, in degrees Celsius;

$T_{14152000}$ is measured water temperature at USGS station 14152000, Middle Fork Willamette River at Jasper, in degrees Celsius; and

$T_{453040123065201}$ is measured water temperature at USGS station 453040123065201, Gales Creek at old Highway 47 in Forest Grove, in degrees Celsius.

Water temperature in the Calapooia River was estimated based on a multiple linear regression between summer LASAR data and two USGS monitoring stations:

$$T_{Calapooia} = 0.660 * T_{14192015} + 0.410 * T_{14152000} \quad (31)$$

where

$T_{Calapooia}$ is estimated water temperature at LASAR site 11182 in the Calapooia River, in degrees Celsius;

$T_{14192015}$ is measured water temperature at USGS station 14192015, Willamette River at Keizer, in degrees Celsius; and

$T_{14152000}$ is measured water temperature at USGS station 14152000, Middle Fork Willamette River at Jasper, in degrees Celsius.

The result from this regression was then adjusted using a warming rate of 0.11 °C/mi applied for 17.1 miles and a lag time of 0.637 days to compute the final estimate of temperature for the Calapooia River.

The water temperature of the Luckiamute River was estimated on the basis of a multiple linear regression between summer LASAR data and several USGS monitoring stations:

$$T_{Luckiamute} = 0.55 * T_{14192015} + 0.25 * T_{453040123065201} + 0.24 * T_{453004122510301} \quad (32)$$

where

$T_{Luckiamute}$ is estimated water temperature in the Luckiamute River based on a correlation with data from LASAR site 10658, in degrees Celsius;

$T_{14192015}$ is measured water temperature at USGS station 14192015, Willamette River at Keizer, in degrees Celsius;

$T_{453040123065201}$ is measured water temperature at USGS station 453040123065201, Gales Creek at old Highway 47 in Forest Grove, in degrees Celsius; and

$T_{453004122510301}$ is measured water temperature at USGS station 453004122510301, Beaverton Creek at 170th Ave in Beaverton, in degrees Celsius.

The water temperature of Rickreall Creek was estimated using a regression between summer 2001 LASAR data and multiple USGS monitoring stations:

$$T_{Rickreall} = 048 * T_{14211550} + 075 * T_{14192015} + 0.28 * T_{14152000} \quad (33)$$

where

$T_{Rickreall}$ is estimated water temperature in Rickreall Creek based on a correlation with LASAR site 11102, in degrees Celsius;

$T_{14211550}$ is water temperature measured at USGS station 14211550, Johnson Creek at Milwaukie, in degrees Celsius;

$T_{14192015}$ is water temperature measured at USGS station 14192015, Willamette River at Keizer, in degrees Celsius; and

$T_{14152000}$ is water temperature measured at USGS station 14152000, Middle Fork Willamette River at Jasper, in degrees Celsius.

The water temperature of point-source discharges to the modeled reaches was provided by ODEQ, obtained from the ECHO database, or taken from the original 2001-2002 models, as described in section “Upper Willamette River Submodel: Temporal Inputs: Flow” above.

The temperature of distributed tributaries used a combination of estimated temperatures and model results from the North Santiam and Santiam River submodel. Distributed tributaries in branches 2 and 3 were assigned temperatures as measured in the Willamette River at Owosso Bridge (USGS station 14158100) minus 0.33 °C to remove the estimated warming from the bottom of the Coast Fork and Middle Fork Willamette River submodel to the monitoring station at Owosso Bridge. Distributed tributaries in branches 4, 5, and 6 were assigned an estimated water temperature meant to be representative of the temperature at the mouth of the McKenzie River; the estimate was computed using a flow-weighted average between temperatures in the Mohawk River and in the McKenzie River at Hayden Bridge, and then applying an average warming rate during summer of 0.11 °C/mi (Rounds, 2010) for 14.8 miles and a travel-time lag of 0.368 days. The distributed tributary in branch 7 was assigned the estimated temperature of the Long Tom River. For branch 8, the distributed tributary was assigned the estimated temperature of the Marys River. Distributed tributaries in branches 9 and 10 were assigned the estimated temperature of the Calapooia River. For branches 11 and 12, the distributed tributaries were assigned the temperature of the outflow from the North Santiam and Santiam River submodel. Lastly, the distributed tributary for branch 13 was assigned the estimated temperature of Rickreall Creek.

Model Fit

Water Balance

The water budget in the Upper Willamette River submodel was balanced using distributed tributaries in branches 2 through 13 (table 2). No distributed flow was applied to branch 1, as described in section “Coast Fork and Middle Fork Willamette River Submodel: Model Fit: Water Balance.” Flow in distributed tributaries 2, 3, and 4 was calculated by comparing the difference in flow between model segment 165 and the measured streamflow at USGS station 14166000 (Willamette River at Harrisburg) and splitting the difference evenly among the three branches. Flow in distributed tributaries 5 through 9 was calculated by evenly dividing the difference between flow in model segment 441 and the measured streamflow at USGS station 14174000 (Willamette River at Albany). Flow in distributed tributaries 10 through 13 was calculated by comparing flow in model segment 666 and the measured streamflow at USGS station 14191000 (Willamette River at Salem) minus the flow from Mill Creek. The streamgage at Salem is located at RM 84.21, which is downstream of the Upper Willamette River submodel domain in the Middle Willamette River submodel. However, because some flow from Mill Creek moves into Pringle Creek, and because Pringle Creek discharges to the Willamette River downstream of the Upper Willamette model boundary and upstream of the Salem streamgaging station, this approach was deemed reasonable. After adjustments with the distributed tributaries to account for ungaged flows, the modeled and measured flows in the Upper Willamette River submodel compare well (fig. 21). In 2016, missing data from streamgaging station EUGO3 in Eugene prevented a comparison of modeled to measured flows in late April and August.

Water Temperature

Continuous water temperature data were available at three locations to check the accuracy of the Upper Willamette River submodel (fig. 20), including at Owosso Bridge in Eugene, at Harrisburg, and at Albany. At Owosso Bridge, the model overestimated diurnal variability but generally replicated the seasonal patterns in stream temperature (fig. 22). The overestimation of diurnal variation in the lower reach of the Coast Fork and Middle Fork submodel and in branch 1 of the Upper Willamette River submodel suggests that the width of the river in this reach might not be represented correctly (perhaps too wide and shallow), or perhaps that the river has some hyporheic flow that dampens the diurnal stream temperature range; however, bathymetric adjustments and research into the existence and magnitude of hyporheic flows were beyond the scope of this study. Model/data agreement is better in spring and early summer than later in the summer and autumn. The subdaily MAE ranges from 0.67 °C in 2011 to 1.01 °C in 2015 (table 3). Model fit improves downstream at Harrisburg (fig. 23) and Albany (fig. 24), with the subdaily MAE at Harrisburg ranging from 0.54 °C in 2011 to 0.74 °C in 2015, and at Albany ranging from 0.53 °C in 2011 to 0.71 °C in 2015. The model reproduces the seasonal and weather-related patterns in water temperature, despite running a little cool toward autumn and sometimes producing a larger-than-measured daily variation.

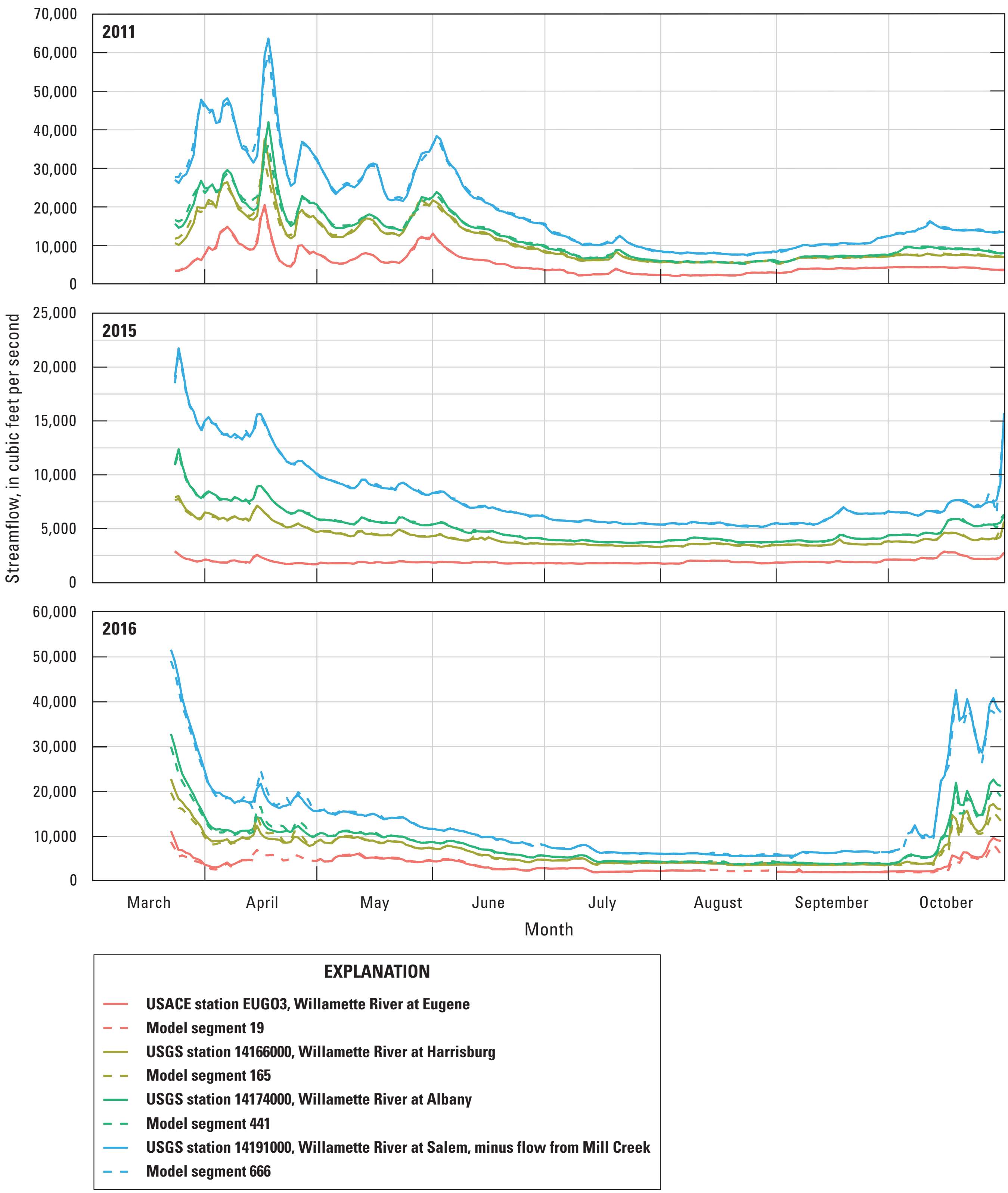


Figure 21. Graphs showing daily modeled streamflow in 2011, 2015, and 2016 from the Upper Willamette River submodel at segments 19, 165, 441, and 666 and measured streamflow at U.S. Army Corps of Engineers (USACE) streamgaging station EUGO3 and at U.S. Geological Survey (USGS) streamgaging stations 14166000 (Willamette River at Harrisburg), 14174000 (Willamette River at Albany), and 14191000 (Willamette River at Salem) minus inflow from Mill Creek, northwestern Oregon. Where not visible, dashed lines are plotted directly over solid lines.

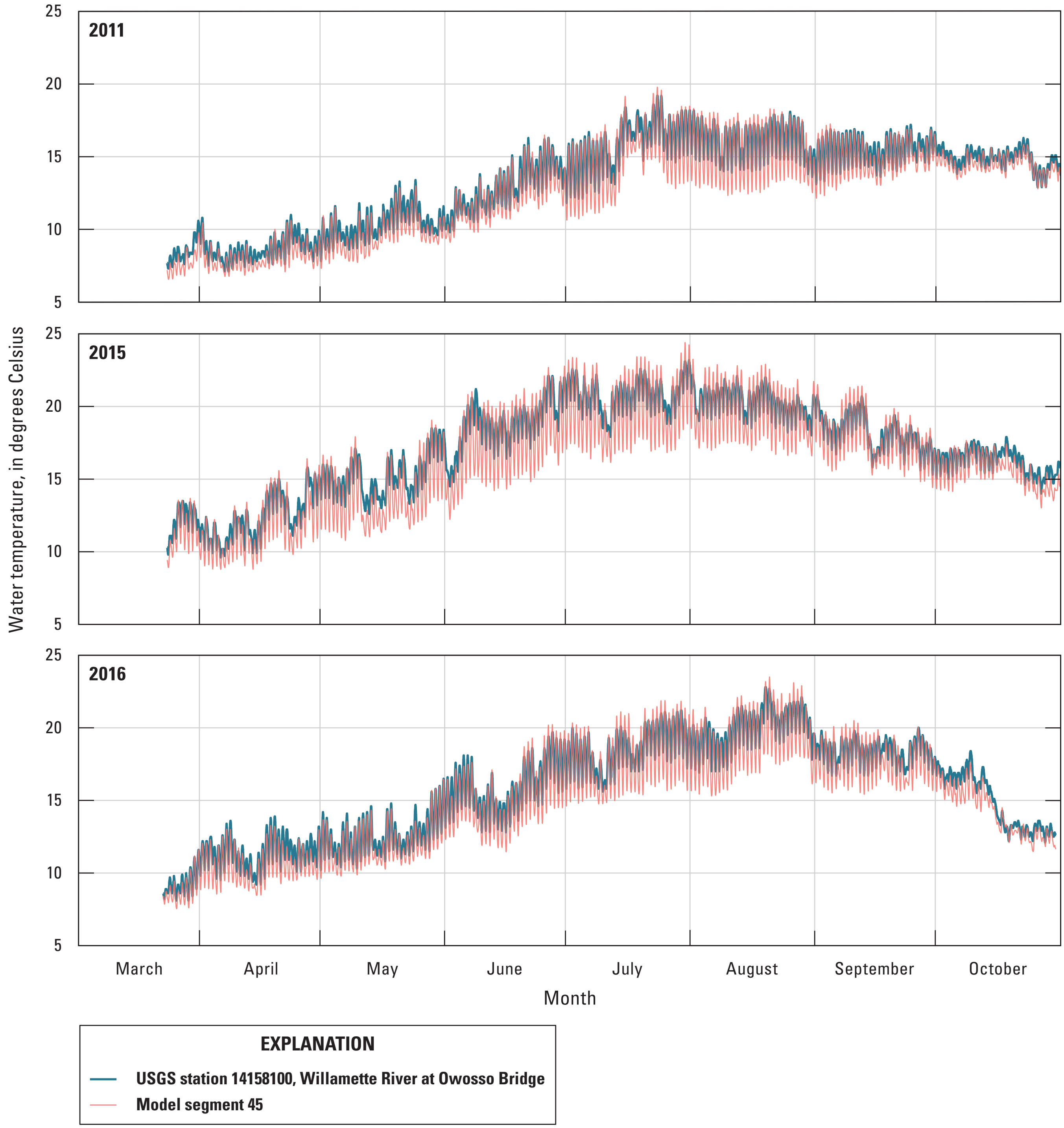


Figure 22. Subdaily modeled water temperature in 2011, 2015, and 2016 from the Upper Willamette River submodel at segment 45 and measured water temperature at U.S. Geological Survey (USGS) station 14158100 (Willamette River at Owosso Bridge), northwestern Oregon.

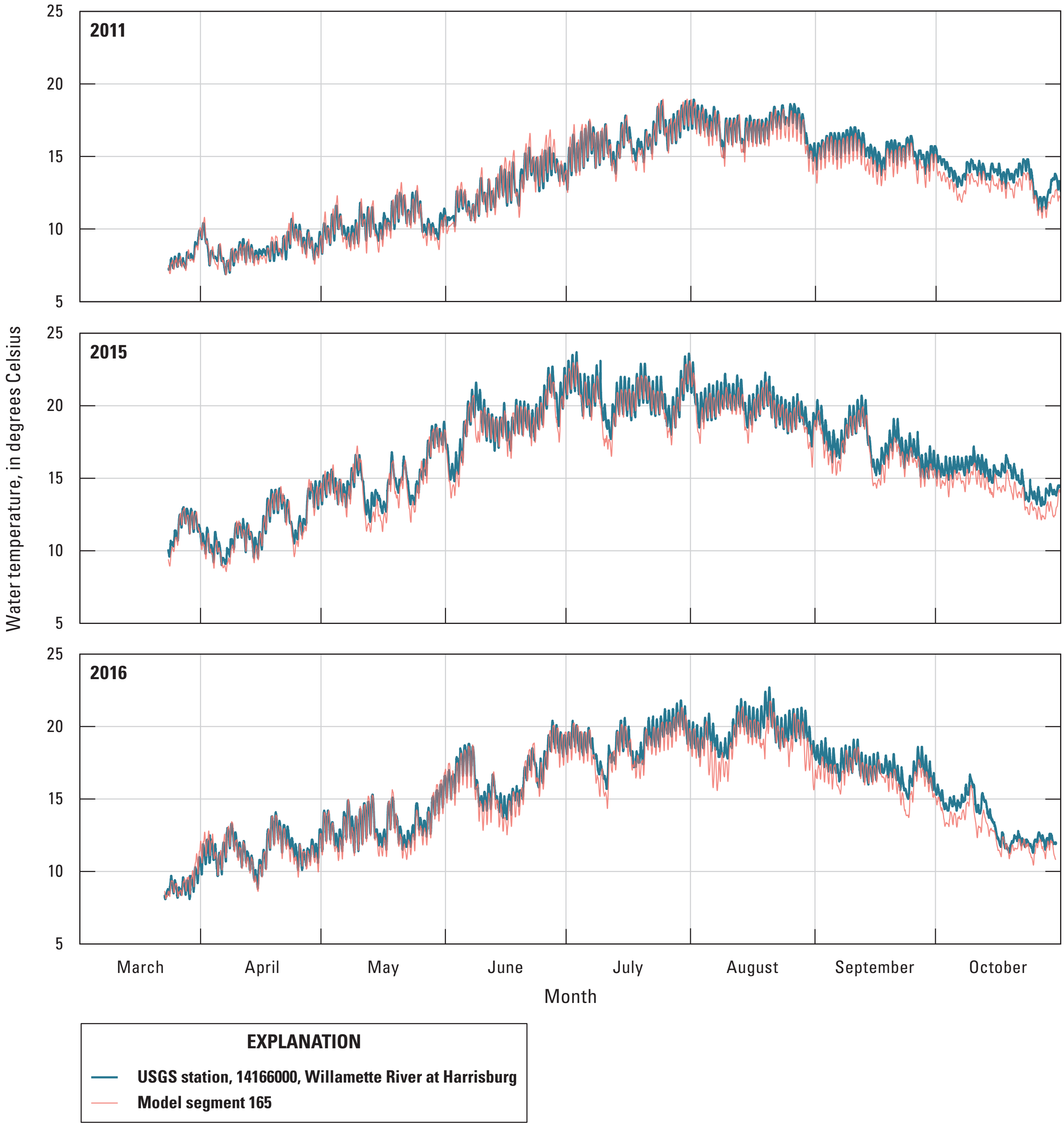


Figure 23. Subdaily modeled water temperature in 2011, 2015, and 2016 from the Upper Willamette River submodel at segment 165 and measured water temperature at U.S. Geological Survey (USGS) station 14166000 (Willamette River at Harrisburg), northwestern Oregon.

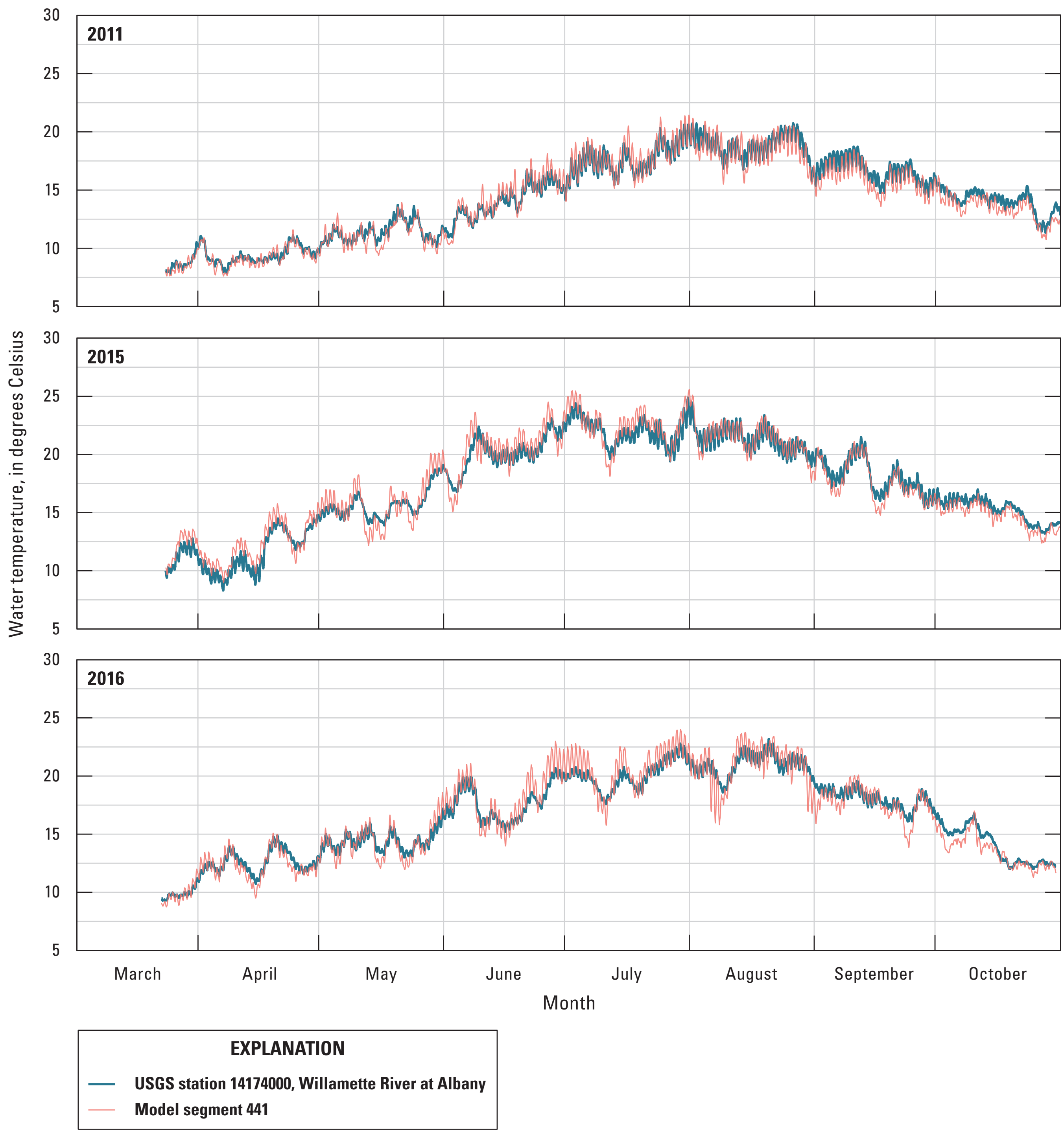


Figure 24. Subdaily modeled water temperature in 2011, 2015, and 2016 from the Upper Willamette River submodel at segment 441 and measured water temperature at U.S. Geological Survey (USGS) station 14174000 (Willamette River at Albany), northwestern Oregon.

Middle Willamette River Submodel

Reach Description

The Middle Willamette River submodel comprises the Willamette River from RM 85.50 at Salem to RM 26.76 at Willamette Falls. From the Santiam River confluence (upstream of the Middle Willamette River submodel, but considered a good boundary between distinct geomorphic reaches of the river) to about RM 50 at Newberg, the Willamette River is generally a single-thread, geologically stable reach with some intermittent gravel bars (Wallick and others, 2013). The river from Newberg to Willamette Falls is generally termed the 'Newberg pool' for the flatwater conditions created by the bedrock sill that is Willamette Falls. The Newberg pool is deep and occasionally stratifies (Mangano and others, 2018). The Middle Willamette River submodel receives input from several tributaries draining the Coast Range or western Willamette Valley, including the Yamhill and Tualatin Rivers. Other tributaries include Mill Creek and the Molalla and Pudding Rivers, which drain the eastern Willamette Valley and lower foothills of the Cascade Range.

Model Domain

The Middle Willamette River submodel consists of six branches comprising three waterbodies (fig. 25). Flow from the Upper Willamette River submodel enters branch 1; the river then flows from branches 1 to 2, 2 to 3, and 3 to 5 before exiting the model at Willamette Falls. Branches 4 and 6 represent river channel features at Wheatland Bar (RM 70.8) and Ash Island (RM 51.5), respectively (Berger and others, 2004). These branches effectively function as alcoves (off-channel habitat with surface connection to the main channel of the river only at the downstream end) in the model. Four tributaries, six point sources, and six withdrawals are included in the model. All withdrawals in the model represent artificial travel-time offsets for the point sources, as described previously.

Bathymetric Grid and Non-Temporal Parameters

No substantive changes to the bathymetric grid were made for the updated model. Willamette Falls is a natural feature in the river, but the height of the geologic sill has been artificially increased to allow for additional head for the production of hydropower. As originally constructed, the Middle Willamette River submodel could be run either with or without the additional 'cap' on the falls. This version of the model uses the model bathymetry that includes the falls cap and thus is representative of current conditions.

Temporal Inputs

All data sources for temporal inputs to the Middle Willamette River submodel are listed in table 1.

Meteorology

Meteorological data for the Middle Willamette River submodel were sourced from Salem Municipal Airport (McNary Field), McMinnville Municipal Airport, Aurora State Airport, and the University of Oregon SRML monitoring site at Portland. All solar radiation inputs were from the SRML Portland record. Waterbody 1 utilized air temperature, dew-point temperature, wind speed, and wind direction data from the Salem Municipal Airport (McNary Field). Waterbody 2 utilized air temperature, dew-point temperature, wind speed, and wind direction data from the McMinnville Municipal Airport. Waterbody 3 utilized air temperature, dew-point temperature, wind speed, and wind direction data from the Aurora State Arport. Cloud cover for all waterbodies was as reported by hourly observation at the respective airports.

Flow

Inflow to the model in branch 1 was the outflow from the Upper Willamette River submodel. Inflows to the upstream ends of branches 4 and 6 (alcoves at Wheatland Bar and Ash Island) were both set to zero. Of the four river tributaries included in the Middle Willamette River submodel, two had available data and two were estimated. Streamflow in the Tualatin River was measured at USGS station 14207500 (Tualatin River at West Linn). Streamflow in Mill Creek near Salem was provided by the City of Salem (J. Boyington and T. Sherman, City of Salem, written commun., 2016). Streamflow in the Yamhill River was estimated using a watershed area approach with the South Yamhill River according to the following equation:

$$Q_{Yamhill} = \left(\frac{772}{528}\right) * Q_{14194150} \tag{34}$$

where

$Q_{Yamhill}$ is estimated streamflow at the mouth of the Yamhill River, in cubic meters per second; and

$Q_{14194150}$ is streamflow measured at USGS station 14194150 (South Yamhill River at McMinnville), in cubic meters per second.

The Pudding River joins the Molalla River just upstream of the Molalla River confluence with the Willamette River, but downstream of the Molalla River streamgaging station. Flow into the model from the Molalla River, therefore, was determined by adding the flow of the Molalla River at USGS station 14200000 to the flow of the Pudding River at USGS station 14202000.

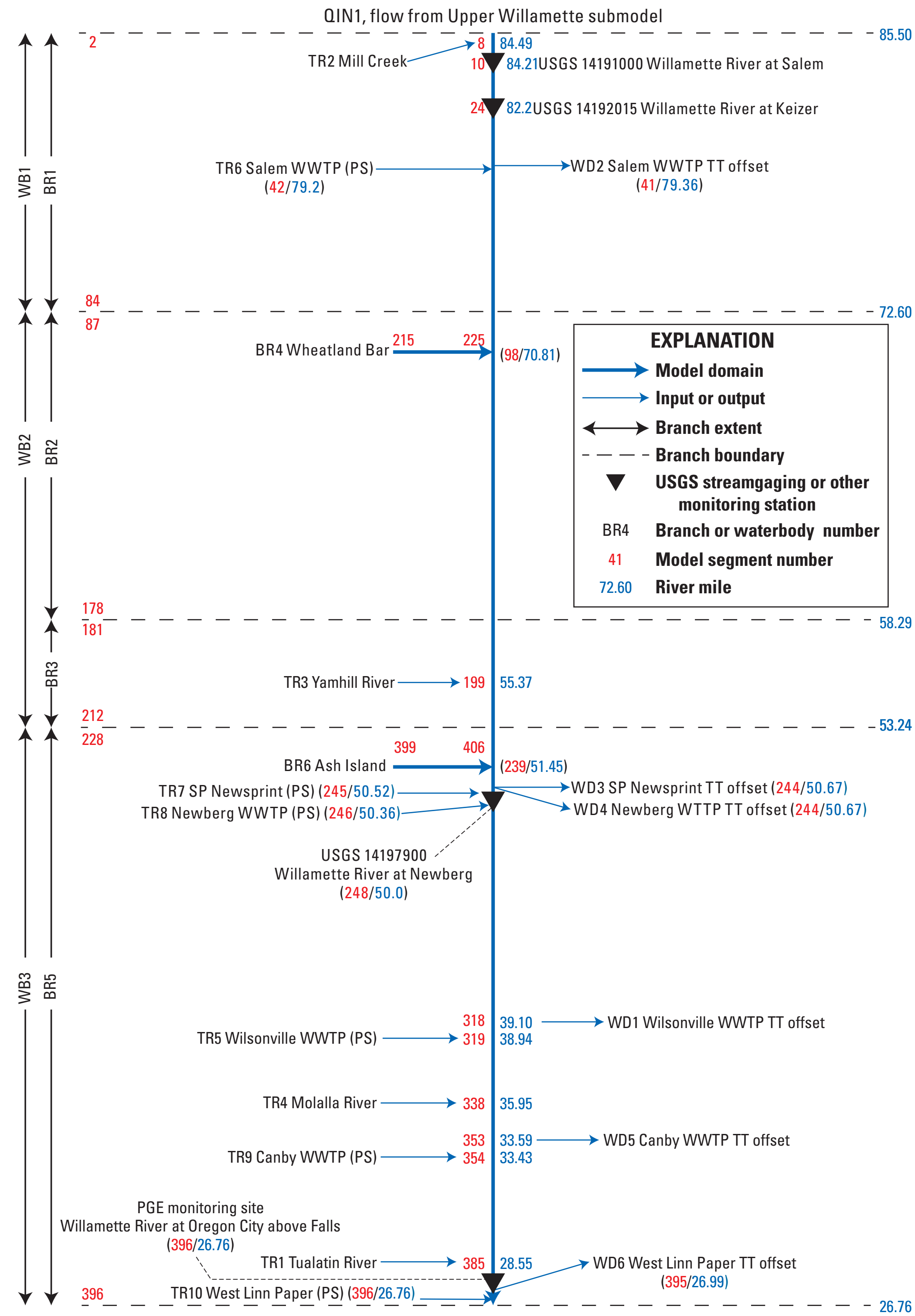


Figure 25. Diagram of the Middle Willamette River submodel, including locations of inflows, withdrawals, branch and waterbody boundaries, and USGS or other relevant streamgaging stations or monitoring sites. Abbreviations: BR, branch; PS, point source; QIN, inflow; TR, tributary; TT, travel time; USGS, U.S. Geological Survey; WB, waterbody; WD, withdrawal; WWTP, wastewater treatment plant.

Tributaries 5 through 10 in the Middle Willamette River submodel are point sources, including the Salem, Newberg, Wilsonville, Canby, and West Linn WWTPs and SP Newsprint (a paper mill). Updated data for SP Newsprint, in Newberg, were not available, so 2001 values were applied. The mill closed in November of 2015; flow inputs after that date were set to zero. Flows and temperatures from the remaining point sources were all updated using data provided by ODEQ. In a few cases, data for 2011, 2015, or 2016 were not available, so data for the closest year for which data were available were applied as a proxy.

All withdrawals included in the Middle Willamette River submodel are travel-time offsets for the point sources.

Water Temperature

Water-temperature boundary conditions for the Middle Willamette River submodel utilized a combination of modeled, measured, and estimated data. Input to the upstream boundary of the submodel was passed from output of the Upper Willamette River submodel. Temperatures for the Tualatin River were taken from measurements at USGS station 14207200 (Tualatin River at Oswego Dam), and temperatures for Mill Creek were provided by the City of Salem. Temperatures in the Yamhill and Molalla Rivers were estimated. The Yamhill River temperature was estimated using a multiple linear regression from summer 2001 LASAR data and USGS measurements as follows:

$$T_{Yamhill} \approx 0.800 * T_{14192015} - 0.070 * T_{14152000} - 0.050 * T_{453040123065201} + 0.8 * T_{453004122510301} \tag{35}$$

where

$T_{Yamhill}$ is estimated water temperature in the Yamhill River based on a correlation with data measured by ODEQ at LASAR site 10363, in degrees Celsius;

$T_{14192015}$ is water temperature measured at USGS station 14192015, Willamette River at Keizer, in degrees Celsius;

$T_{14152000}$ is water temperature measured at USGS station 14152000, Middle Fork Willamette River at Jasper, in degrees Celsius;

$T_{453040123065201}$ is water temperature measured at USGS station 453040123065201, Gales Creek at old Highway 47 in Forest Grove, in degrees Celsius; and

$T_{453004122510301}$ is water temperature measured at USGS station 453004122510301, Beaverton Creek at 170th Ave in Beaverton, in degrees Celsius.

From this regression, a warming rate of 0.11 °C/mi was applied for 5 miles with a 0.186 day time lag to estimate the temperature input for the Yamhill River.

A similar approach was used to estimate the water temperature of the Molalla River, using the following regression model:

$$T_{Molalla} \approx 0.67 * T_{14211550} + 0.93 * T_{14192500} - 0.61 * T_{14152000} \tag{36}$$

where

$T_{Molalla}$ is estimated water temperature of the Molalla River, based on a correlation with data from ODEQ LASAR site 32059, in degrees Celsius;

$T_{14211550}$ is water temperature measured at USGS station 14211550, Johnson Creek at Milwaukie, in degrees Celsius;

$T_{14192500}$ is water temperature measured at USGS station 14192500, South Yamhill River near Willamina, in degrees Celsius; and

$T_{14152000}$ is water temperature measured at USGS station 14152000, Middle Fork Willamette at Jasper, in degrees Celsius.

The temperature of point sources to the model was provided by ODEQ, obtained from the ECHO database, or taken from the original 2001-2002 models, as described previously in section, “Middle Willamette River Submodel: Temporal Inputs: Flow.”

The water temperature of distributed tributaries was assigned using the measured or estimated temperature of nearby monitoring stations (after Annear and others, 2004). The distributed tributary for branch 1 was assigned the temperature of Mill Creek. Distributed tributaries for branches 2, 3, and 5 were assigned the estimated temperature of the Yamhill River.

Model Fit

Water Balance

Measured streamflow data to check and calibrate the water balance were available at two locations within the Middle Willamette River submodel domain. Streamflow from USGS station 14191000 (Willamette River at Salem) was compared to flow from segment 10, near the upstream boundary of the submodel, to confirm that inflow from the Upper Willamette River submodel was reasonably correct. Distributed tributary flows in branches 1, 2, and 3 (fig. 25) were apportioned from the difference between daily streamflow from USGS station 14197900 (Willamette River at Newberg) and daily streamflow at segment 248 of the model. No streamflow measurements were available downstream of Newberg. Distributed tributary flow was applied to branch 5 using a watershed area ratio between the Pudding River at Aurora (USGS station 14202000) and the ungaged watershed area in the Middle Willamette River submodel, weighted for the proportional linear distance of the Willamette River from

Newberg to Willamette Falls relative to the entire Middle Willamette River submodel (table 2). This method was applied in the original development of the Middle Willamette River submodel (Annear and others, 2004). No distributed flow was applied to branches 4 or 6, which effectively act as alcoves in the model. To prevent unreasonable oscillations in the computed flows for distributed tributaries, the flow differences computed for distributed tributary flows were smoothed using a 2-day moving average. After the adjustments to the distributed tributaries, the modeled and measured streamflow for the Middle Willamette River submodel compared reasonably well, as expected (fig. 26).

Water Temperature

Two continuous and one daily water-temperature monitoring datasets were available in the domain of the Middle Willamette River submodel. Of the submodels included in this report, the goodness-of-fit for water temperature in the Middle Willamette River submodel is among the best. At Keizer (segment 24, RM 82.2; fig. 25), the model replicated subdaily water temperatures with a MAE ranging from 0.48 °C in 2016 to 0.62 °C in 2015 (fig. 27; table 3). Downstream at Newberg, the fit was similar (fig. 28; table 3). No continuous water temperature data were available at Willamette Falls, but the Oregon Department of Fish and Wildlife collects water temperature readings on a daily basis at the Willamette Falls fish ladder (K. Melchar, Oregon Department of Fish and Wildlife, written commun., 2020). The fish ladder, however, was not simulated explicitly in the model and temperatures in the fish ladder, which draws water from near the surface of the river and therefore may be warmer than water at depth in summer, are likely to be warmer than the well-mixed average temperature exiting the model at Willamette Falls. Because of this lack of a true comparison of measured and simulated temperatures in the fish ladder, and because the data at Willamette Falls are daily and do not meet USGS data-quality standards, no goodness-of-fit statistics were calculated and comparisons at this location should be considered a non-authoritative check on model output; however, the model appears to reasonably approximate patterns in the measured stream temperature at a daily or weekly time scale (fig. 29). Future updates to the Middle Willamette River submodel and related river monitoring might benefit from a more explicit representation of the fish ladder in the model, along with installation of a high-quality continuous water-temperature sensor at Willamette Falls.

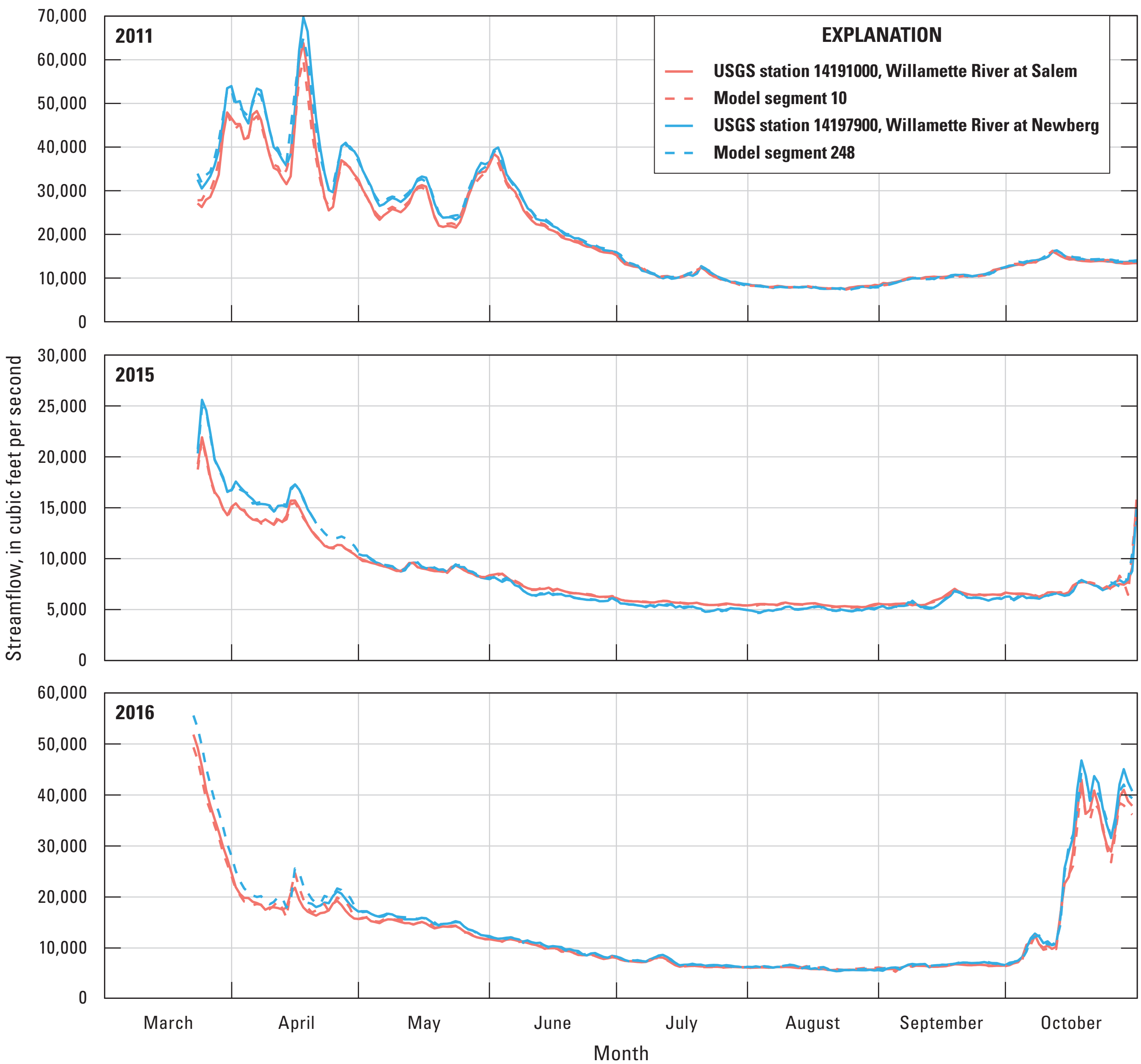


Figure 26. Daily modeled streamflow in 2011, 2015, and 2016 from the Middle Willamette River submodel at segments 10 and 248 and measured streamflow at U.S. Geological Survey (USGS) streamgaging stations 14191000 (Willamette River at Salem) and 14197900 (Willamette River at Newberg), northwestern Oregon. Where not visible, dashed lines are plotted directly over solid lines. Data from USGS streamgaging station 14197900 in 2016 were missing from the start of the modeling period until April 19th.

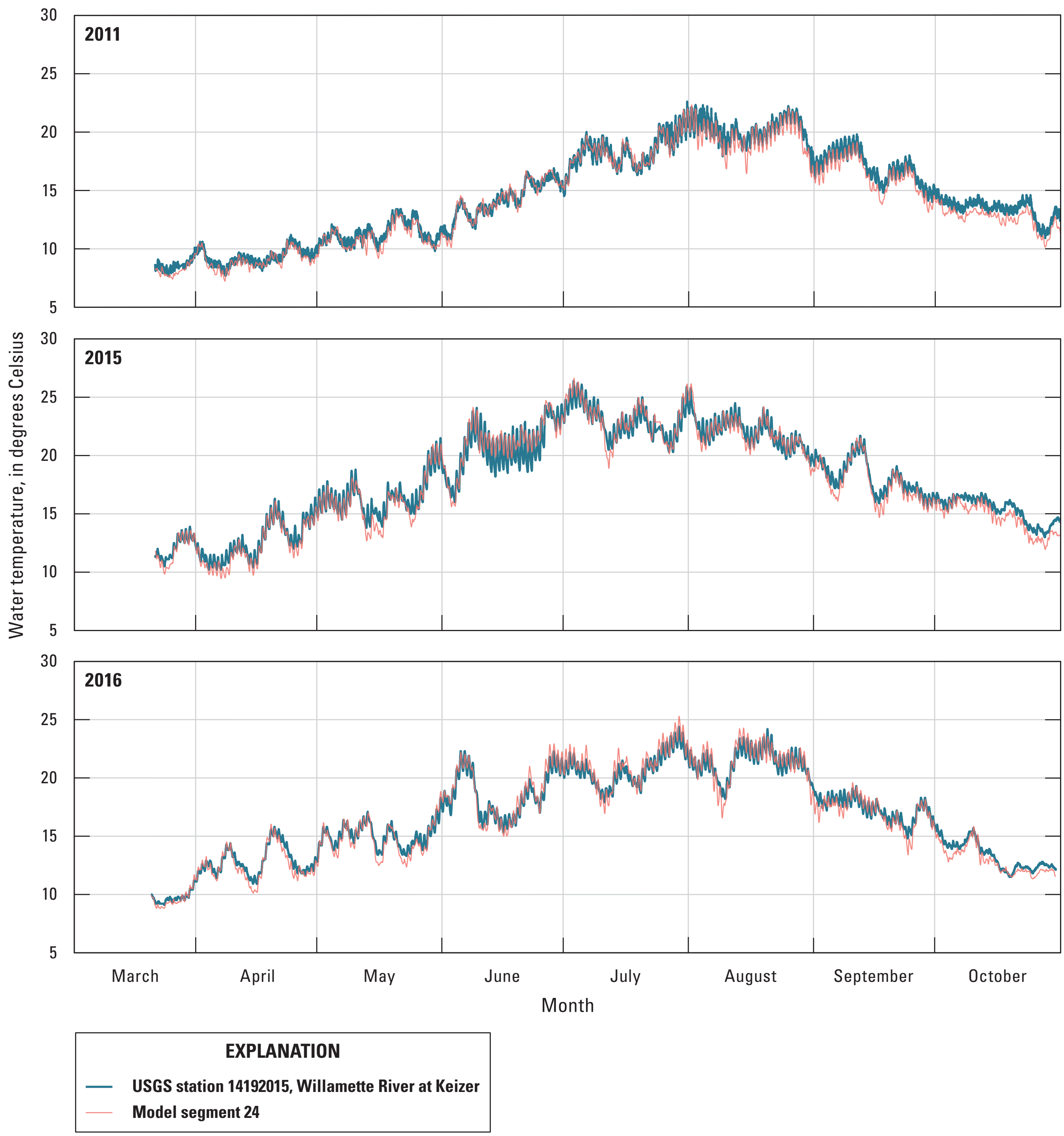


Figure 27. Subdaily modeled water temperature in 2011, 2015, and 2016 from the Middle Willamette River submodel at segment 24 and measured water temperature at U.S. Geological Survey (USGS) station 14192015 (Willamette River at Keizer), northwestern Oregon.

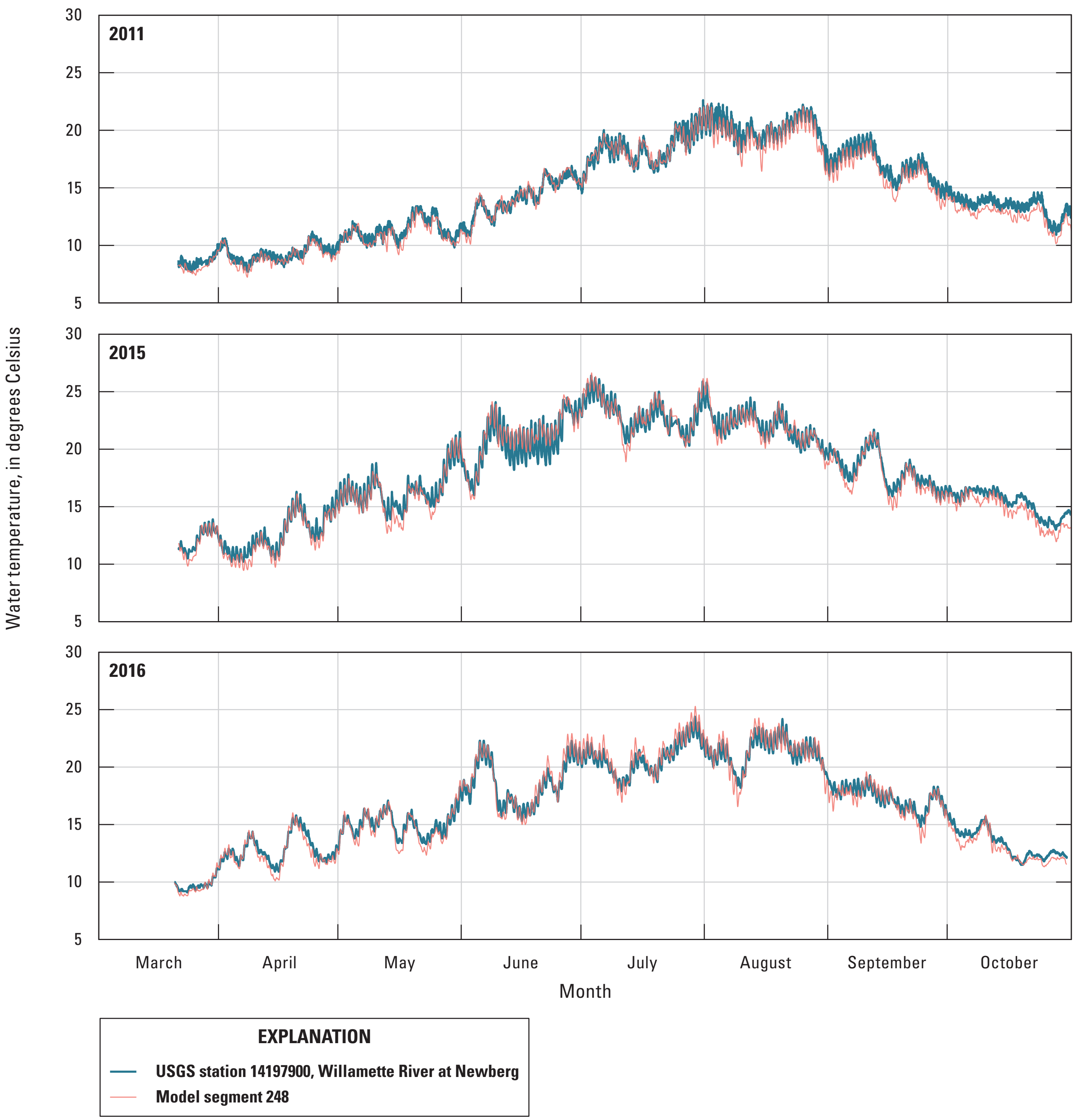


Figure 28. Subdaily modeled water temperature in 2011, 2015, and 2016 from the Middle Willamette River submodel at segment 248 and measured water temperature at U.S. Geological Survey (USGS) station 14197900 (Willamette River at Newberg), northwestern Oregon.

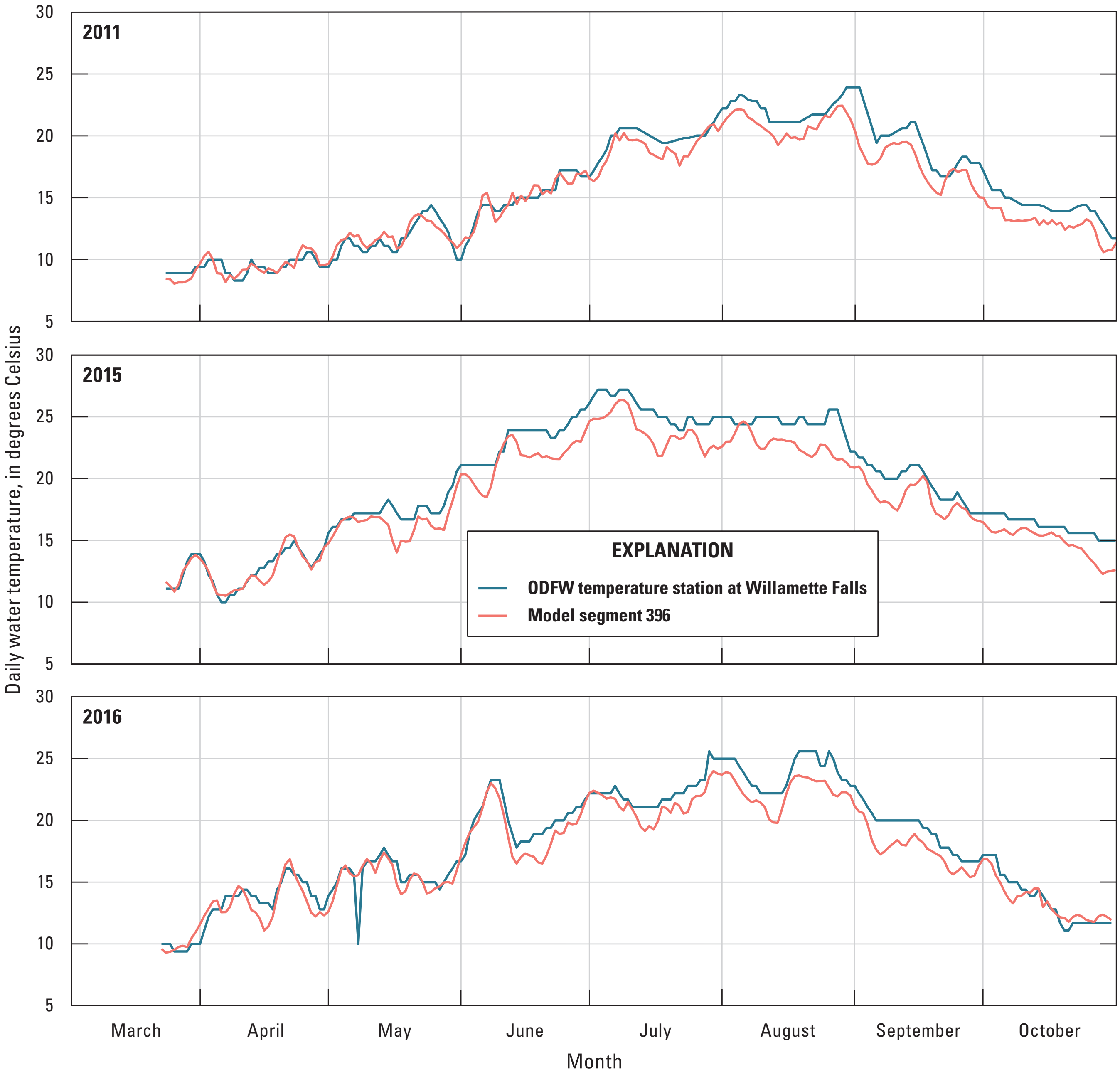


Figure 29. Daily-averaged modeled water temperature in 2011, 2015, and 2016 from the Middle Willamette River submodel at segment 396 and measured water temperature recorded in the morning, typically around 7 a.m., at Willamette Falls, northwestern Oregon. ODFW, Oregon Department of Fish and Wildlife.

Summary and Possible Future Research

This report documents the modernization to version 4.2 (with modifications by the U.S. Geological Survey) and the configuration of a set of CE-QUAL-W2 models (developed by other researchers) to simulate streamflow and water temperature in the Willamette River and several of its major tributaries for late March through October in three years: 2011 (a "cool, wet" year), 2015 (a "hot, dry" year), and 2016 (a more-"normal" year). Submodels described in this report include models of the Coast Fork and Middle Fork Willamette River, McKenzie River, South Santiam River, North Santiam and Santiam River, Upper Willamette River, and Middle Willamette River. All models were originally developed and calibrated for 2001 and 2002 using a modification of CE-QUAL-W2 version 3.12. As part of this update, some model parameters were adjusted to improve model stability or decrease runtimes, improve model fit, and better reflect current conditions. Additionally, in the Coast Fork and Middle Fork Willamette River and the McKenzie River submodels, artificial tributaries used to balance the water budget were removed and replaced with distributed tributaries to better simulate the spatial distribution of ungaged gains or losses of flow in the models.

The updated models documented in this report will enable the U.S. Army Corps of Engineers, as well as other agencies and researchers, to simulate thermal conditions in the Willamette River Basin across a range of climatic and streamflow conditions and to investigate the potential thermal effects of management changes to the flow regime on threatened fish populations. As these models continue to be utilized, they may be further refined and adjusted as additional data are collected, or as new features are added to the model code. Some of the submodels may merit refinement of model parameters to continue to increase their stability and accuracy across a range of conditions and to further decrease the time required for them to run. With the exception of the South Santiam River submodel for 2011, all of the submodels reproduce the measured water-temperature patterns and magnitudes at the location of continuous water-temperature monitors with reasonable accuracy (less than about 1.0 °C and nearing 0.5 °C as a mean absolute error).

Although the overall goodness-of-fit statistics are acceptable, several issues should be considered when interpreting results of simulations made with these models. First, with some exceptions, the models predict daily mean water temperatures more accurately than the corresponding daily minima or maxima. Generally, the CE-QUAL-W2 submodels documented in this report tend to overestimate diurnal variation. This is probably due to the model's inability to simulate hyporheic flow, which tends to buffer daily temperature variations. For, example, the inability to model hyporheic flow in the lower reaches of the Santiam River was noted earlier as one potential reason that the model overpredicted the amount of daily temperature variation. This hypothesis may also apply to other locations within the model domain where the river is dynamic and has abundant gravel substrate (for example, the Willamette River in Eugene near Owosso Bridge; or other dynamic reaches of the river upstream of Corvallis). Second, the Coast Fork and Middle Fork Willamette River submodel tends to have a negative bias (simulated temperatures that are too cool). This suggests that width-to-depth ratios may need refinement for this submodel, as the ratios used may represent too little exposure to solar radiation. This negative bias may be an artifact of the channel simplification required by CE-QUAL-W2. Unfortunately, the Coast Fork and Middle Fork Willamette River submodel has only a small amount of data available for calibration for the years 2011, 2015, and 2016, which limits any efforts to better understand the spatial variability of model fit or refine model inputs or bathymetry. The South Santiam River submodel also suffers from a paucity of data that could be used to further explore any bias in that model or to refine its calibration.

Although a few new streamgaging stations and water temperature datasets were available to support modeling for the years 2011, 2015, and 2016, fewer data in general were available to drive the model boundary conditions or to check model accuracy relative to 2001 and 2002. As a result, data from different locations had to be used, or methods to estimate boundary conditions had to be developed, to update the models for 2011, 2015 and 2016. These changes, along with minor physical changes to the river system between 2002 and 2016, may reduce the accuracy of the model output. Despite those changes and potential effects on model accuracy, however, the submodels still produced results that met the informal accuracy criterion of a typical mean absolute error of less than 1.0 °C. This highlights the fact that, while CE-QUAL-W2 is capable of accurate subdaily estimates of stream temperature because of its mechanistic approach, it requires large quantities of data to build and calibrate the model. Future applications of the model would benefit from the installation of new high-quality water temperature sensors at key locations, such as at Willamette Falls and at the mouth of the South Santiam River. For these models to be useful to simulate conditions in future years, it is important to maintain the network of long-term, continuous streamflow, meteorological, and stream temperature records at key locations throughout the study area.

Supplementary Material

The models documented in this report are available at https://doi.org/10.5066/P908DXKH (Stratton Garvin and Rounds, 2021).

References Cited

Anderson, B., Peng, R., and Ferreri, J., 2016, Package 'weathermetrics': Github, accessed May 4, 2020, at https://github.com/geanders/weathermetrics/.

Annear, R.L., McKillip, M.L., Khan, S.J., Berger, C.J., and Wells, S.A., 2004, Willamette River Basin temperature TMDL model—Boundary conditions and model setup: Portland, Oregon, Portland State University, Department of Civil and Environmental Engineering, Technical Report EWR-01-04, 530 p.

Berger, C.J., McKillip, M.L., Annear, R.L., Khan, S.J., and Wells, S.A., 2004, Willamette River Basin temperature TMDL model—Model calibration: Portland, Oregon, Portland State University, Department of Civil and Environmental Engineering, Technical Report EWR-02-04, 341 p.

Bloom, J.R., 2016, South Santiam River, Oregon—Hydrodynamics and water temperature modeling, 2000–2002: Portland, Oregon Department of Environmental Quality, 53 p.

Branscomb, J., Goicochea, M., and Richmond, 2002, Stream Network, *in* D. Hulse, S. Gregory, and J. Baker (eds.), Willamette River Basin planning atlas (2nd ed): Corvallis, Oregon State University Press, accessed September 3, 2020, at https://oregonexplorer.info/data_files/OE_location/willamette/documents/3b.strm_network_web.pdf.

Buccola, N.L., Rounds, S.A., Sullivan, A.B., and Risley, J.C., 2012, Simulating potential structural and operational changes for Detroit Dam on the North Santiam River, Oregon, for downstream temperature management: U.S. Geological Survey Scientific Investigations Report 2012–5231, 68 p.[Also available at https://doi.org/10.3133/sir20125231.]

Buccola, N.L., 2017, Water temperature effects from simulated changes to dam operations and structures in the Middle and South Santiam Rivers, Oregon: U.S. Geological Survey Open-File Report 2017–1063, 19 p. [Also available at https://doi.org/10.3133/ofr20171063.]

Buccola, N.L., Risley, J.C., and Rounds, S.A., 2016, Simulating future water temperatures in the North Santiam River, Oregon: Journal of Hydrology, v. 535, p. 318–330. [Also available at https://doi.org/10.1016/j.jhydrol.2016.01.062.]

Buccola, N.L., Stonewall, A.J., and Rounds, S.A., 2015, Simulations of a hypothetical temperature control structure at Detroit Dam on the North Santiam River, northwestern Oregon: U.S. Geological Survey Open–File Report 2015-1012, 30 p. [Also available at https://doi.org/10.3133/ofr20151012.]

Buccola, N.L., Stonewall, A.J., Sullivan, A.B., Kim, Y., and Rounds, S.A., 2013, Development of CE-QUAL-W2 models for the Middle Fork Willamette and South Santiam Rivers, Oregon: U.S. Geological Survey Open-File Report 2013–1186, 55 p. [Also available at https://doi.org/10.3133/ofr20131186.]

Bureau of Reclamation, 2020, Pacific Northwest Region–Agri-Met: Bureau of Reclamation, accessed August 4, 2020, at https://www.usbr.gov/pn/agrimet/.

Caissie, D., 2006, The thermal regime of rivers—A review: Freshwater Biology, v. 51, no. 8, p. 1389–1406, accessed September 9, 2021, at https://doi.org/10.1111/j.1365-2427.2006.01597.x.

Callaghan, E., and Buddington, A.F., 1938, Metalliferous mineral deposits of the Cascade Range in Oregon: U.S. Geological Survey Bulletin 893, 141 p., accessed February 14, 2022, at https://doi.org/10.3133/b893.

Church, M., 1988, Floods in cold climates, *in* Baker, V.R., Kochel, R.C., and Patton, P.C., eds., Flood geomorphology: New York, Wiley, p. 205–229.

Cole, T.M., and Wells, S.A., 2017, A two-dimensional, laterally averaged, hydrodynamic and water quality model, version 4.1: Portland State University, Oregon, Department of Civil and Environmental Engineering, [variously paged].

Conlon, T.D., Wozniak, K.C., Woodcock, Douglas, Herrera, N.B., Fisher, B.J., Morgan, D.S., Lee, K.K., and Hinkle, S.R., 2005, Groundwater hydrology of the Willamette Basin, Oregon: U.S. Geological Survey Scientific Investigations Report 2005–5168, 83 p.[Also available at https://pubs.usgs.gov/sir/2005/5168.]

Emerson, D.G., Vecchia, A.V., and Dahl, A.L., 2005, Evaluation of drainage-area ratio methjod used to estimate streamflow for the Red River of the North Basin, North Dakota and Minnestona: U.S. Geological Survey Scientific Investigations Report 2005–5017, 13 p., accessed September 9, 2021, at https://doi.org/10.3133/sir20055017.

Gregory, S.V., Ashkenas, Linda, and Nygaard, Chris, 2007, Summary report to assist development of ecosystem flow recommendations for the Coast Fork and Middle Fork of the Willamette River, Oregon: Institute for Water and Watersheds, Oregon State University, 237 p. [Also available at https://ir.library.oregonstate.edu/concern/defaults/44558j63k.]

H.J. Andrews Experimental Forest Long-Term Ecological Research Network, 2020, Primary meteorological station (PRIMET)—Elev 430m: Portland, Oregon State University, accessed August 4, 2020, at https://andrewsforest.oregonstate.edu/data/streaming/meteorological-stations/primary-meteorological-station-primet-elev-430m.

Hinkle, S.R., Duff, J.H., Triska, F.J., Laenen, A., Gates, E.B., Bencala, K.E., Wentz, D.A., and Silva, S.R., 2001, Linking hyporheic flow and nitrogen cycling near the Willamette River–A large river in Oregon, USA: Journal of Hydrology, v. 244, no. 3-4, p. 157–180. [Also available at https://doi.org/10.1016/S0022-1694(01)00335-3.]

Jefferson, A., Grant, G., and Rose, T., 2006, Influence of volcanic history on groundwater patterns on the west slope of the Oregon High Cascades: Water Resources Research, v. 42, no. 12, W12411, accessed September 9, 2021, at https://doi.org/10.1029/2005WR004812.

Keefer, M.L., Taylor, G.A., Garletts, D.F., Gauthier, G.A., Pierce, T.M., and Caudill, C.C., 2010, Prespawn mortality in adult spring Chinook salmon outplanted above barrier dams: Ecology Freshwater Fish, v. 19, no. 3, p. 361–372, accessed September 9, 2021, at https://doi.org/10.1111/j.1600-0633.2010.00418.x.

Lawrence, M.G., 2005, The relationship between relative humidity and the dewpoint temperature in moist air—A simple conversion and applications: Bulletin of the American Meteorological Society, v. 86, no. 2, p. 225–234, accessed September 9, 2021, at https://doi.org/10.1175/BAMS-86-2-225.

Mamoon, M., 2016, Stream temperature modeling for Marys River Watershed: Oregon State University master's thesis, accessed September 1, 2020, at https://ir.library.oregonstate.edu/concern/graduate_thesis_or_dissertations/sn00b1176.

Mangano, J.F., Piatt, D.R., Jones, K.L, and Rounds, S.A., 2018, Water temperature in tributaries, off-channel features, and main channel of the lower Willamette River, northwestern Oregon, summers 2016 and 2017: U.S. Geological Survey Open-File Report 2018–1184, 33 p., accessed August 15, 2020, at https://doi.org/10.3133/ofr20181184.

National Marine Fisheries Service, 2008, Willamette Basin biological opinion—Endangered Species Act Section 7(a)(2) consultation: National Oceanic and Atmospheric Administration Fisheries Log Number F/ NWR/2000/02117 [variously paged]. [Also available at https://www.fisheries.noaa.gov/resource/document/consultation-willamette-river-basin-flood-control-project.]

National Centers for Environmental Information, 2020, NOAA National Centers for Environmental Information integrated surface database: National Oceanic and Atmospheric Administration, accessed May 4, 2020, at https://www.ncei.noaa.gov/access/search/data-search/global-hourly.

National Centers for Environmental Information Web Services, 2020, Local climatological data (LCD) dataset documentation: National Oceanic and Atmospheric Administration, 13 p., accessed August 4, 2020, at https://www1.ncdc.noaa.gov/pub/data/cdo/documentation/LCD_documentation.pdf.

Olden, J.D., and Naiman, R.J., 2010, Incorporating thermal regimes into environmental flows assessments—Modifying dam operations to restore freshwater ecosystem integrity: Freshwater Biology, v. 55, no. 1, p. 86–107, accessed September 9, 2021, at https://doi.org/10.1111/j.1365-2427.2009.02179.x.

Oregon Department of Environmental Quality, 2003, Figure 340A—Fish use designations, Willamette Basin, Oregon: Oregon Department of Environmental Quality, accessed October 23, 2019, at https://www.oregon.gov/deq/FilterRulemakingDocs/figure340a.pdf.

Oregon Department of Environmental Quality, 2005, Draft revised Figure 340B—Salmon and steelhead spawning use designations, Willamette Basin, Oregon: Oregon Department of Environmental Quality, accessed October 23, 2019, at https://www.oregon.gov/deq/FilterRulemakingDocs/figure340b.pdf.

Oregon Department of Environmental Quality, 2020a, Ambient water quality monitoring system: Oregon Department of Environmental Quality, accessed August 4, 2020, at https://www.oregon.gov/deq/wq/pages/wqdata.aspx.

Oregon Department of Environmental Quality, 2020b, Water quality standards—Beneficial uses, policies, and criteria for Oregon—Temperature: Oregon Department of Environmental Quality, Oregon Administrative Rule 340-041-0028(4), accessed January 30, 2020, at https://secure.sos.state.or.us/oard/viewSingleRule.action?ruleVrsnRsn=244176.

PRISM Climate Group, Oregon State University, 2020, PRISM climate data: Corvallis, Prism Climate Group, Oregon State University website, accessed April 28, 2020, at http://www.prism.oregonstate.edu.

Risley, J., Wallick, J.R., Waite, I., and Stonewall, A., 2010a, Development of an environmental flow framework for the McKenzie River Basin, Oregon: U.S. Geological Survey fvestigations Report 2010–5016, 94 p. [Also available at https://doi.org/10.3133/sir20105016].

Risley, J.C., Constantz, J.A., Essaid, H.I., and Rounds, S.A., 2010b, Effects of upstream dams versus groundwater pumping on stream temperature under varying climate conditions: Water Resources Research, v. 46, no. 6, accessed September 9, 2021, at https://doi.org/10.1029/2009WR008587.

Risley, J.C., Wallick, J.R., Mangano, J.F., and Jones, K.L., 2012, An environmental streamflow assessment for the Santiam River Basin, Oregon: U.S. Geological Survey Open-File Report 2012–1133, 66 p. [Also available at https://doi.org/10.3133/ofr20121133].

Rounds, S.A., 2007, Temperature effects of point sources, riparian shading, and dam operations on the Willamette River, Oregon: U.S. Geological Survey Scientific Investigations Report 2007–5185, 34 p. [Also available at https://doi.org/10.3133/sir20075185.]

Rounds, S.A., 2010, Thermal effects of dams in the Willamette River basin, Oregon: U.S. Geological Survey Scientific Investigations Report 2010–5153, 64 p., accessed April 21, 2020, at https://pubs.usgs.gov/sir/2010/5153/.

Smith, C.D., Mangano, J.F., and Rounds, S.A., 2020, Temperature and water-quality diversity and the effects of surface-water connection in off-channel features of the Willamette River, Oregon, 2015–16: U.S. Geological Survey Scientific Investigations Report 2020–5068, 70 p., accessed September 9, 2021, at https://doi.org/10.3133/sir20205068.

Stratton Garvin, L.E., and Rounds, S.A., 2022, CE-QUAL-W2 models for the Willamette River and major tributaries below U.S. Army Corps of Engineers dams—2011, 2015, and 2016: U.S. Geological Survey Data Release, https://doi.org/10.5066/P908DXKH.

Sullivan, A.B., and Rounds, S.A., 2004, Modeling streamflow and water temperature in the North Santiam and Santiam Rivers, Oregon, 2001–02: U.S. Geological Survey Scientific Investigations Report 2004–5001, 35 p. [Also available at https://doi.org/10.3133/sir20045001].

Tague, C., and Grant, G., 2004, A geological framework for interpreting the low-flow regimes of Cascade streams, Willamette River Basin, Oregon: Water Resources Research, v. 40, no. 4, W04303, accessed September 9, 2021, at https://doi.org/10.1029/2003WR002629.

U.S. Army Corps of Engineers, 2019, Willamette Valley system operations and maintenance environmental impact statement (EIS) scoping informational brochure: U.S. Army Corps of Engineers, 15 p., accessed August 4, 2020, at https://usace.contentdm.oclc.org/digital/collection/p16021coll7/id/11455.

U.S. Army Corps of Engineers, 2020, Dataquery 2.0: U.S. Army Corps of Engineers, accessed August 4, 2020, at https://www.nwd-wc.usace.army.mil/dd/common/dataquery/www/.

U.S. Environmental Protection Agency, 2020, Enforcement and compliance history online: U.S. Environmental Protection Agency, accessed August 4, 2020, at https://echo.epa.gov/.

U.S. Geological Survey, 2020a, National Water Information System: U.S. Geological Survey, accessed August 4, 2020, at https://doi.org/10.5066/F7P55KJN.

U.S. Geological Survey, 2020b, USGS data grapher: U.S. Geological Survey, accessed August 4, 2020, at https://or.water.usgs.gov/grapher/.

U.S. Geological Survey, 2020c, StreamStats: U.S. Geological Survey, accessed August 4, 2020, at https://streamstats.usgs.gov/ss/.

University of Oregon, 2020, Solar radiation monitoring laboratory data source: Eugene, University of Oregon, accessed May 4, 2020, at http://solardat.uoregon.edu/.

Venables, W.N., and Ripley, B.D., 2002, Modern applied statistics with S (4th ed.): Springer, New York, 495 p., accessed September 9, 2021, at https://doi.org/10.1007/978-0-387-21706-2.

Wallick, J.R., Jones, K.L., O'Connor, J.E., Keith, M.K., Hulse, D., and Gregory, S.V., 2013, Geomorphic and vegetation processes of the Willamette River floodplain, Oregon–Current understanding and unanswered questions: U.S. Geological Survey Open–File Report 2013-1246, 70 p. [Also available at https://doi.org/10.3133/ofr20131246.]

Wells, S.A., ed., 2019, CE-QUAL-W2—A two-dimensional, laterally averaged, hydrodynamic and water quality model, version 4.2: Portland State University, Oregon, Department of Civil and Environmental Engineering, [variously paged].

Wentz, D.A., Bonn, B.A., Carpenter, K.D., Hinkle, S.R., Janet, M.L., Rinella, F.A., Uhrich, M.A., Waite, I.R., Laenen, A., and Bencala, K.E., 1998, Water quality in the Willamette Basin, Oregon, 1991–95: U.S. Geological Survey Circular 1161, 34 p. [Also available at https://pubs.usgs.gov/circ/circ1161].

Western Regional Climate Center, 2020, RAWS USACE climate archive: Reno, Nevada, Desert Research Institute, accessed May 4, 2020, at http://www.raws.dri.edu.

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